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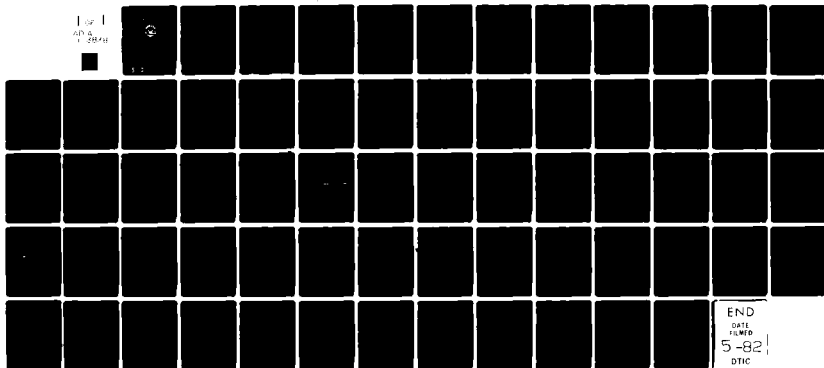
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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

A STUDY OF HORIZONTAL SEA SURFACE TEMPERATURE
VARIABILITY

by

William Aubrey Butler

December 1981

Thesis Advisors:

Roland W. Garwood, Jr.
Edward B. Thornton

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A113 F38	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Study of Horizontal Sea Surface Temperature Variability		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis December, 1981
7. AUTHOR(s) William Aubrey Butler		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE December, 1981
		13. NUMBER OF PAGES 65
		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Sea Surface Temperature, Horizontal Temperature Variability, Temperature Spectra, Temperature Patchiness, Temperature Variance, Ocean Thermal Structure, Mesoscale Temperature Variability		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The horizontal variability of "patchiness" in sea surface temperature structure is examined on length scales between 0.6 and 76.8 kilometers. A primary purpose was to test the hypothesis that atmospheric forcing is a cause of horizontal temperature variance on these length scales. Using continuous sea surface temperatures acquired in the Central North Pacific Ocean, spectra were computed for temperature variance. The variability in these spectra on seasonal, synoptic, and diurnal periods was then examined and correlated with changes in atmospheric conditions. Important results found included a		

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A Study of Horizontal Sea Surface Temperature Variability

by

William Aubrey Butler
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1971

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY
AND OCEANOGRAPHY

from the
NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The horizontal variability of "patchiness" in sea surface temperature structure is examined on length scales between 0.6 and 76.8 kilometers. A primary purpose was to test the hypothesis that atmospheric forcing is a cause of horizontal temperature variance on these length scales. Using continuous sea surface temperatures acquired in the Central North Pacific Ocean, spectra were computed for temperature variance. The variability in these spectra on seasonal, synoptic, and diurnal periods was then examined and correlated with changes in atmospheric conditions. Important results found included a seasonal dependence for the patchiness structure, a negative correlation between surface temperature variance and wind speed on a synoptic time scale, and a diurnal variability in patchiness that may be explained by solar insolation and turbulent heat exchange with the atmosphere. In conclusion, a strong atmospherically controlled temporal variability in the small scale horizontal sea surface temperature variance is found and may explain inconsistencies in earlier observational and theoretical studies.

TABLE OF CONTENTS

I.	INTRODUCTION -----	12
A.	BACKGROUND -----	12
B.	PURPOSE OF STUDY -----	14
C.	PREVIOUS STUDIES OF HORIZONTAL VARIABILITY IN SST -----	16
1.	Overview -----	16
2.	Individual Studies -----	20
3.	Need for a Unifying Study -----	26
II.	ASSEMBLING AND ORDERING OF DATA SETS -----	27
A.	DATA ACQUISITION -----	27
B.	DATA ASSEMBLY -----	28
C.	ATMOSPHERIC DATA -----	30
D.	ERRORS IN THE DATA -----	32
III.	STATISTICAL ANALYSIS PROCEDURES -----	33
A.	SPECTRUM ANALYSIS AND DATA FILTERING -----	33
B.	SPECTRAL ESTIMATES AND ENSEMBLE AVERAGING -----	36
C.	PROCESSING INITIAL TEST SPECTRA: 0.6 TO 76.8km -----	37
D.	FINAL SPECTRA PROCESSING: 0.64 TO 9.6km -----	41
IV.	DISCUSSION OF RESULTS -----	43
A.	GENERAL STRUCTURE OF PATCHINESS -----	43
B.	SEASONAL VARIABILITY IN TEMPERATURE VARIANCE -----	44
C.	DAY-TO-DAY VARIABILITY IN TEMPERATURE VARIANCE -----	47
D.	DIURNAL VARIABILITY IN TEMPERATURE VARIANCE -----	58
V.	CONCLUSIONS AND RECOMMENDATIONS -----	60

BIBLIOGRAPHY	-----	62
INITIAL DISTRIBUTION LIST	-----	64

LIST OF TABLES

TABLE

I.	Review of Complex Ocean Temperature Structures -----	13
II.	Review of Different Studies in SST Variability -----	18
III.	Review of Representative Theoretical Studies of Wave Number Dependence for Ocean Temperature Variance -----	19

LIST OF FIGURES

FIGURE

1. "Smooth" surface temperature field: little or no patchiness on a km scale -----	15
2. "Patchy" surface temperature field: strong variability on a small scale -----	15
3. Example of trackline position for each minute SST observation for Julian date 99 -----	29
4. Example of daily plot of SST along trackline shown in Figure 3 -----	29
5. Method of linear interpolation from equal time to equal space -----	31
6. Total temperature perturbation along trackline -----	34
7. Large scale component of temperature perturbation along trackline ($>10\text{km}$) -----	34
8. Small scale component of temperature perturbation along trackline ($<10\text{km}$) -----	35
9. Average temperature variance spectrum: spring -----	38
10. Average temperature variance spectrum: summer -----	38
11. Four-hour temperature spectra depiction with two degrees of freedom -----	40
12. Four-hour temperature spectra depiction with sixteen degrees of freedom -----	42
13. Comparison of average summer and spring spectra -----	45
14. Average daily temperature variance at $k=1\text{ km}^{-1}$ for each day of data -----	46
15. Spectral slope for average daily spectra for each day of data ----	48
16. Diurnal variation in SST spectra for wave number $k=.65\text{ km}^{-1}$: spring conditions-----	49
17. Diurnal variation in SST spectra for wave number $k=.65\text{ km}^{-1}$: summer conditions-----	50

FIGURE

18.	Diurnal variation in SST spectra for wave number $k=9.8 \text{ km}^{-1}$: spring conditions -----	51
19.	Diurnal variation in SST spectra for wave number $k=9.8 \text{ km}^{-1}$: summer conditions -----	52
20.	Correlation between changing temperature variance and changing wind speed: Julian days 1-100 -----	54
21.	Correlation between changing temperature variance and changing wind speed: Julian days 180-230 -----	55
22.	Correlation between changing temperature variance and changing cloud cover: Julian days 1-100 -----	56
23.	Correlation between changing temperature variance and changing cloud cover: Julian days 180-230 -----	57

NOTATION

a_k, b_k	Fourier coefficients from fast Fourier transform
C	Temperature in degrees centigrade
cm	Centimeter
Δk	Resolution of spectra
Δx	Spacing between observations
$E_T(k)$	Temperature variance density as a function of wave number
FFT	Fast Fourier Transform
k	wave number in cycles/km
km	Kilometer
km^{-1}	cycles/kilometer
m	meters
SST	Sea Surface Temperature

ACKNOWLEDGMENTS

The author wishes to express appreciation to Dr. R. W. Garwood and Dr. E. B. Thornton, Department of Oceanography, Naval Postgraduate School, for their time, interest, and guidance throughout this study. Gratitude is also expressed to Dr. C. N. K. Mooers for his helpful discussions and review of this thesis.

Finally, I am truly grateful to my wife, Cathy, and to my son and daughter for their patience, understanding and encouragement, and without whose help this paper would never have been completed.

I. INTRODUCTION

A. BACKGROUND

The study of ocean characteristics has long been of interest to men of the sea. Early mariners were the first to discover that prevailing winds and ocean currents could aid their transits to and from different parts of the world. These phenomena were carefully noted in ship's logs and passed on from navigator to navigator so that maximum benefit could be made of environmental conditions. Early seafarers also noted that conditions were continually changing. Although a clockwise circulation was typically found in the Atlantic, anomalous storms and wave conditions could greatly modify these conditions on time scales from diurnal to seasonal. These men learned more about the sea with each voyage, but it seemed that the variability and complexity of the sea increased in proportion to the quantity of observational data. One reason for this was that the conditions expected by the early mariners were based on observations of limited regions of the ocean that included the main trade routes.

The modern day oceanographer faces the same problems as the early mariners in trying to predict the ocean's various physical properties. Studies of the ocean's physical characteristics have increased with the advent of modern sensors such as CTD's, expendable bathythermographs, and various satellite radiometers. Nevertheless, the explanation of the complexity of the ocean's thermal structure still largely remains a mystery. As shown by Table I on ocean fine structure from Federov [1978], the

TABLE I - REVIEW OF COMPLEX OCEAN TEMPERATURE STRUCTURES

STRUCTURAL ELEMENT	OBSERVED VERTICAL SCALE (M)	OBSERVED HORIZONTAL SCALE (KM)	COMMENTS
1. Quasi- uniform layers and laminae	30-40	180-250	In layers 300-400M
	10-20	30-50	In layers 100-300M
	10-15	100	In layers 50-500M
	2-30	2-20	In layers 1-40M
	15	13	
	1-2	1.5	
	.1	.2	
	2.5	17	Double diffusive convection
2. Micro steps in temperature "sheets"	1.0	.75	In layers 0-100M
	.1-3.5	.2	In layers deeper than 400M
	.1	.05-.2	
	.1-.15	17	Double diffusive convection
3. Temperature inversions	10-100	5-10	
	5-20	5-20	
	5-10	"a few miles"	
4. Advective iso- anomolies	10-20	10-15	

greater the quantity of ocean temperature data and the finer the resolution, the more complex the spatial structure appears.

B. PURPOSE OF STUDY

The purpose of this thesis is to examine the horizontal variability in sea surface temperature (SST) along ship tracklines. Federov [1978] has shown that the temperature structure is a highly variable physical characteristic in both the horizontal and vertical as shown in Table I. The horizontal variability in sea surface temperature over small distances (10^2 - 10^4 m) shall be called here "temperature patchiness." This study primarily focuses on the scales between 0.6km and 10km, and the results are shown to be different from earlier findings for larger scales. Figures 1 and 2 illustrate just how "patchy" the ocean surface temperature can be on these scales. This thesis will examine the horizontal variability in sea surface temperature at scales less than about 10 kilometers (km) and greater than 600 meters (m).

The temperature patchiness is first examined by spectrum analysis to determine its structure over a range of space scales. From this study, the change in variability on seasonal and daily scales will be examined to determine a possible correlation with atmospheric forcing by the wind stress, surface heat fluxes, and solar radiation.

The working hypothesis for this study is that atmospheric forcing strongly influences the small scale SST variability. Both mechanical forcing by the wind and thermodynamic forcing by radiative and turbulent heat flux at the air-sea interface are expected to be contributing factors.

CENTRAL NORTH PACIFIC SST TRACE - WINTERTIME

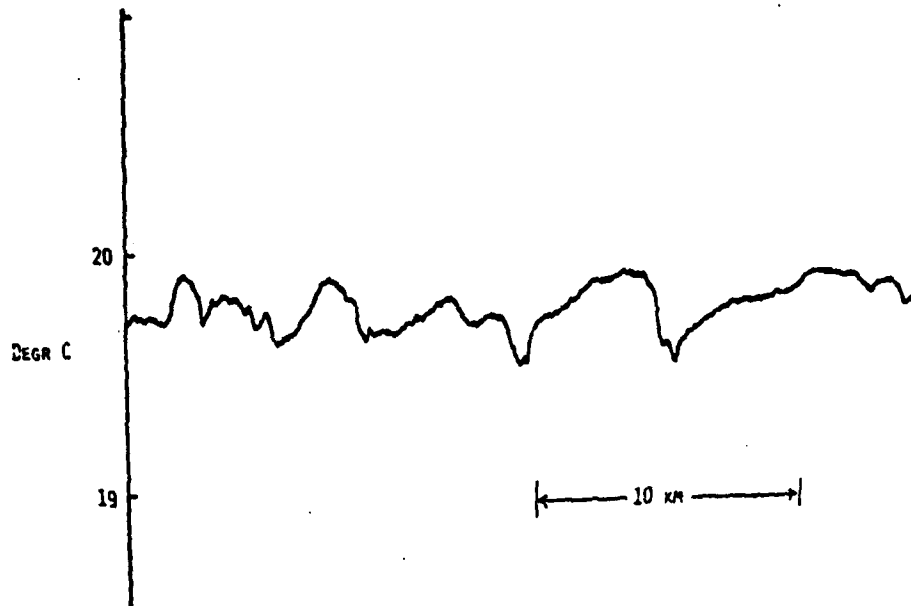


FIGURE 1. "SMOOTH" SURFACE TEMPERATURE FIELD: LITTLE OR NO
PATCHINESS ON A 10 KM SCALE
CENTRAL NORTH PACIFIC SST TRACE - WINTERTIME

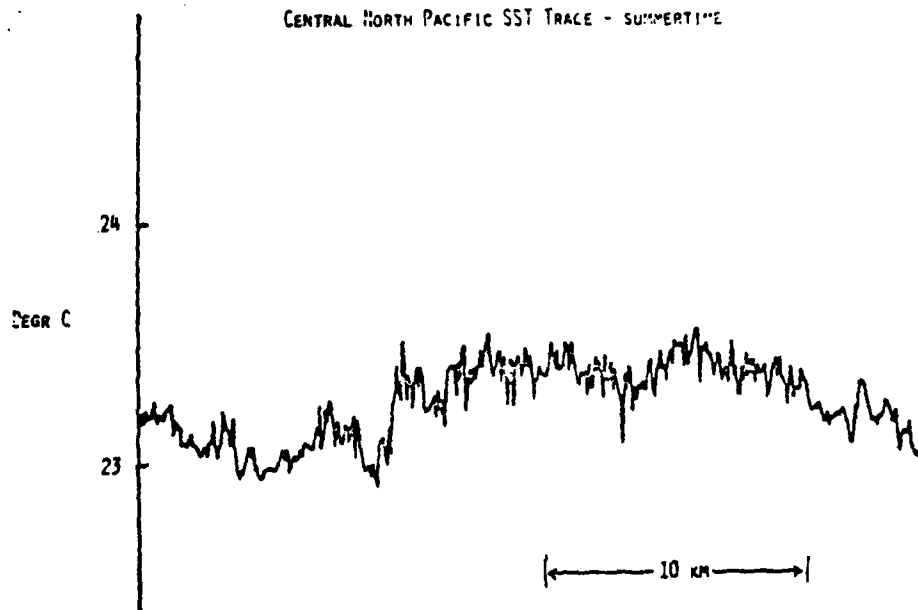


FIGURE 2. "PATCHY" SURFACE TEMPERATURE FIELD: STRONG
VARIABILITY ON A SMALL SCALE

An ultimate goal for this research is the formulation of a model for SST patchiness as a function of atmospheric forcing. This model could then be used to provide second order statistics (such as thermal variance $\overline{T'^2}$) in conjunction with the first order variables (SST and mixed layer depth) from a mixed layer model. [Garwood, 1979] The long-range goal for modeling of this kind is to produce thermal structure analyses and forecast products which could be used in conjunction with various underwater detection systems currently being used by the Navy. The use of a strictly homogeneous ocean temperature structure in the horizontal is a simplification that frequently cannot give realistic results for the underwater acoustic problem. The better the ocean can be modeled, the better environmentally sensitive systems can be used by the Navy.

C. PREVIOUS STUDIES OF HORIZONTAL VARIABILITY IN SST

1. Overview

SST variability has been of interest to oceanographers for many years. Means for rapidly acquiring sea surface temperature data over a large area have not been available until recently. Climatology has been frequently used as the only available representation of the temperature structure both horizontally and vertically. Most oceanographers realize this is an oversimplification but it is frequently the only recourse available. Climatology is based on all types of inputs such as ship intake temperatures, bathythermographs, buoy data and ship bucket temperatures. In other words, any observation available is normally used. Unfortunately, the sea is much more complex than climatology and second order statistics such as patchiness are not normally included.

Several studies have been undertaken since the early 1960's to examine how the surface temperature structure changes and why it changes. Most studies have covered very limited areas of the ocean and specific spatial scales of variability. Table II provides a chronology of various studies that have been conducted. The biggest differences among these are the methods of data collection and the scales studied. Studies by McLeish [1970], Saunders [1972], Holladay and O'Brien [1975], Fieux, et al [1978], and Deschamps, et al [1981] are particularly significant, but are somewhat inconclusive. As shown by Table II, there is substantial disagreement among the investigators. One needs to compare the results of these observational studies with the theoretical predictions listed in Table III. The basis for comparison between the various experiments and theories is the constant wave number power law fall off in temperature variance density. The different results show a fall off in temperature variance that is proportional to an increase in wave number to the power $(-n)$, or:

$$E_T(k) \propto k^{-n} \quad (1)$$

where $E_T(k)$ is the one dimensional temperature variance density spectrum in units of C^2 -km, k is cycles/km, and n is a dimensionless constant.

The spectrum for thermal variance has frequently been assumed to have a functional dependence upon wave number that was similar to that for the spectrum for kinetic energy. The problem in dealing with temperature variance density on scales less than 100 km is that this regime is still considered to be in the domain of "unresolved motion" on a large scale as reported by Woods [1976]. In other words, there is no well-accepted theory that can explain the variability in temperature that is observed

TABLE II - REVIEW OF DIFFERENT STUDIES IN SST VARIABILITY

AUTHOR(S)	HORIZONTAL RANGE OF SCALES (KM)	POWER LAW EXPONENT K^{-n} (n)	SOURCE OF DATA
1. Lafond and Lafond [1966]	5-70	5/3	Result of internal forcing (as reported by McLeish)
2. Voorhis and Perkins [1966]	.3-5	5/3	Drogue measurement at 99M
3. Williams [1968]	.01-10	5/3	Measured on FLIP at 30M
4. McLeish [1970]	3-50 less than 3	5/3 0	Surface and airborne radiometer measurements
5. Saunders [1972]	3-100	2.2	Airborne radiometer measurements
6. Lilly and Lester [1974]	4-20	3	Atmospheric temperature
7. Holladay and O'Brien [1975]	3-20	3	Airborne radiometer measurements
8. Fieux (et al) [1978]	1-64	2	Ship bucket tempera- tures and satellite data
9. Deschamps (et al) [1981]	3-100	1.5- 2.3	Satellite data

TABLE III - REVIEW OF REPRESENTATIVE THEORETICAL STUDIES OF WAVE NUMBER
DEPENDENCE FOR OCEAN TEMPERATURE VARIANCE

AUTHOR(S)	THEORETICAL POWER LAW EXPONENT K^{-n} (n)	THEORETICAL BASIS
1. Kolmogorov [1941]	5/3	3 dimensional isotropic turbulence theory
2. Bolgiano [1962]	1.4	3 dimensional/stratifica- tion dominated/turbulence theory $E_{ke}(k) \propto E_T(k)$
3. Phillips [1966]	1	3 dimensional/stratifica- tion dominated/turbulence theory
4. Kraichnan [1967]	1	2 dimensional isotropic turbulence theory $E_T(k)$ (passive contaminant)
5. Charney [1971]	3	2 dimensional quasi- geostrophic turbulence theory
6. Garrett and Munk [1972]	2	Internal wave forcing
7. Lilly and Lester [1974]	3	3 dimensional atmospheric turbulence theory $E_T(k) \propto E_{ke}(k)$

on scales less than the Rossby radius of deformation. Nevertheless, these different studies give an idea of the variability that has been found on different horizontal scales.

2. Individual Studies

McLeish [1970] attempted to determine on what horizontal scales the temperature variations became significant. He used both ship and aircraft radiometric observations from the 7-12 micron infrared (IR) band. He then calculated temperature variance spectra using the autocovariance technique of Blackman and Tukey [1958]. The data was low pass filtered to reduce aliasing, and mean instrument noise for the radiometer was subtracted from all spectra. All observations were taken under similar atmospheric conditions at various times of the year. Neither time of day nor season of the year seemed to have any influence on his results. Bulk SST's were also recorded by the ship for calibration of the radiometers. Errors considered to be present in the spectra were either instrument induced or from atmospheric contamination.

McLeish [1970] found a maximum spectral density at the smallest wave numbers and a wave number power law dependence of $k^{-5/3}$. This was in agreement with three dimensional turbulence theory proposed by Kolmogorov [1941] for the inertial subrange. However, his calculated spectra values flattened out at an amplitude of $.1 \text{ C}^2\text{-cm}$ at wave numbers between 2 and 5 km^{-1} or length scales of about 2-3 km. This was the first reported observation of a flattening in the spectra at higher wave numbers. McLeish did not believe that this feature was turbulence related, but due to differences between skin temperature structure and the structure as measured a few centimeters below the surface. He also believed that

2

convergence slicks can form on the sea surface which change the sea surface temperature by the inhibition of heat transport to the surface from below which can lead to temperature differences of up to 1°C on very small scales.

Stommel and Federov [1967] saw a similar structure in the oceanic temperature patterns at many different depths. They labeled these patchiness patterns as structure laminae with horizontal length scales between 2 and 20 km and vertical scales of 2 to 40 meters. They believed that this form of patchiness was most likely related to vertical mixing processes. Such processes may include mechanical mixing from the wind, breaking internal waves, and convective mixing from density instabilities which are related to temperature fluxes at the air-ocean interface and solar radiational effects.

Saunders [1972] conducted a similar study of temperature structure in the upper regions of the Ionian Sea. The purpose of his experiment was to describe the temperature pattern present and to determine the different causes of such patterns. Using radiometric techniques similar to those of McLeish, he observed SST from an aircraft. For comparison, ship observations were taken over a 250km by 220km area enabling two-dimensional SST contour plots to be constructed. Comparisons were made with ocean station data to determine the possible causes of the patchiness structure, examining in particular the geostrophic flow and general circulation through the area. This information was used to describe advective effects in the temperature change process. He noted that advection is not uniform and other complexities in the ocean structure, such as small scale geostrophic flows and wind induced frictional motion, will tend to

distort the isotherm patterns and lead to a variable temperature structure. He further stated that the temperature variance field probably cascades from large scales to small scales. This is analogous to turbulence theory and the cascade of energy from low wave numbers to high wave numbers in the inertial range.

Saunders attempted to verify the cascade theory of temperature variance by statistical analysis of the data. He detrended the data by least square fit and computed spectra over several tracklines of data. The result was a fall off of temperature variance with increasing wave number similar to that of McLeish but with a $k^{-2.2}$ dependence which did not fit any of the previously proposed models for geophysical turbulence as listed in Table III. He concluded that no theory has been accurate in predicting the temperature variance structure due to the complexity of geophysical processes. A variety of theories may be required to explain all scales. Saunders suggested the large scales will be controlled by rotational effects and small scales by stratification.

The temperature variance was found to be in an equilibrium state over the three-week time period covered by this experiment. By using a "filtered correlation" technique, Saunders found that the longer the wave length or length scale, the more persistent the temperature variance density, with scales of 25km lasting 2-5 days and scales of 100km lasting 8-16 days. He concluded that the observed time scales of temperature variance were not turbulence-related but resulted from advection by mesoscale features imbedded in the mean flow which are presumed larger than turbulence scales.

Holladay and O'Brien [1975] conducted a study of small scale temperature variability in the upwelling zone off the coast of Oregon. The study examined the mesoscale air-sea interaction in an upwelling region as a function of wind forcing and resulting temperature fields. The study area including both the coastal upwelling and the open ocean domains were presumed to be isotropic and controlled by wind forcing. IR radiometer data were acquired daily during the months of July and August from low flying aircraft. Ground truth was simultaneously acquired by fishing vessels using the bucket temperature method. Computer analyzed daily SST maps were produced by digitizing the data to a one-kilometer grid of the area, and thereby forming two dimensional depictions of SST. Simultaneous wind data were acquired over the area to study the response to wind forcing of the daily SST fields.

The initial results clearly showed the effects of upwelling on the SST patterns with relatively cool temperatures near the coast. The decreases in temperature were directly related to the magnitude and direction of wind which could cause a mass transport of surface water away from the coast for a northerly wind and result in upwelling. Fronts were also observed in the data that were thought to be a result of surface convergence. The characteristic that is of particular interest here is that these fronts were found on a scale of hundreds of meters and not on a much larger scale as previously thought. The fronts seemed to be formed and advected by the upwelling process which resulted in local daily changes in the SST of as much as 5°C. Holladay and O'Brien also determined variance spectra for their data. First, the three-week mean was removed from the SST grid to produce daily perturbation fields.

Two-dimensional spectra were computed using a two-dimensional fast Fourier transform. The two-dimensional spectrum densities were integrated with respect to direction to obtain one-dimensional spectra of the data as a function of wave number. Their results showed a k^{-3} power law fall off for wave numbers between 4km^{-1} and 25km^{-1} . Since Charney [1971] indicated the (-3) fall off might apply to strong baroclinic zones in the ocean, his theory might be applied in the 7-20km range (corresponding to the Rossby radius of deformation). However, Charney's geostrophic turbulence theory does not consider advection in and out of the area of interest. Holladay and O'Brien suggest other possible influences on small scale SST variability including solar heating, precipitation, cloud cover, and air-sea temperature differences and conclude that further research is required to determine their effects.

Fieux, et al [1978] attempted to correlate small scale SST structures and currents in the Gulf of Leon. The data were acquired from ships, satellite radiometers, and buoys, and all sources were combined to give a single representation of a two-dimensional SST field. Currents were simultaneously measured from meters on buoys strategically placed in the experiment area. The results showed that the satellite data did not resolve diurnal changes in the SST patterns that could be seen in the shipboard observations. Also, shipboard and buoy observations were hard to compare due to the different depth of sensors. The ship observations were taken every 2.5km and the temperature variance density spectra computed. The fall off of temperature variance density with increasing wave number was once again observed with an exponent of -2 in the length scale range of 5-80km. The most significant result of this study was the lack of

correlation of the currents with the SST structure. The lack of correlation could be explained if the predominant currents in the area were geostrophic with flow parallel to the isotherms. However, wind-induced currents should probably have an impact by advection as suggested by Holladay and O'Brien.

Deschamps, et al [1981], using IR data from various polar orbiting satellites, tested the feasibility of using satellite derived SST data for examining mesoscale SST structures. The resolution of the satellite was typically $.1^{\circ}\text{C}/\text{km}^2$ for the area under the nadir of the radiometer. This resolution was thought to be sufficient for the scales involved. The idea of using the satellite was based on the need for observing SST over large areas in a short period of time. Assuming the temperature fields to be random, Deschamps, et al computed statistics on the temperature variance density, thus providing information on the scales and magnitudes of the temperature variability. They computed temperature variance spectra by use of a Fourier transform method and obtained the best fit for the k^{-p} power law as before. Two range scales were examined: 40-100km and 3-30km. In both ranges, the value of the exponent (p) varied from 1.5 to 2.3 with a mean of 1.9 for large scales and 1.8 for the smaller scales. They found no geographic or seasonal dependence. These results compare favorably with the results reported by Saunders, [1972] and Fieux, et al [1978].

In comparing the results to turbulence theory, Deschamps, et al encountered the same difficulty in looking for a theory that can explain the fall off of variance in this range of scales. Causes of temperature variability on these scales remain undetermined. Possible sources of

energy and corresponding scales include wind waves (100m), atmospheric systems (1000km) and baroclinic instability based on the internal radius of deformation (10-50km in the open ocean), none of which can be completely responsible for such structures. It is believed that turbulence theory has failed because of differences between geophysical and hypothetical conditions. Further observational studies and more realistic theoretical studies are needed to explain the small scale variability.

3. Need for a Unifying Study

Based on inconsistencies found in the literature, there is a need for a closer examination of sea surface patchiness structure at smaller spatial and temporal scales. By resolving the temporal variability of horizontal patchiness, an explanation of the diversified results from observed and theoretical studies may be possible.

II. ASSEMBLING AND ORDERING OF DATA SETS

A. DATA ACQUISITION

The data used in this study were acquired by the USNS Silas Bent between April 1976 and August 1977 during operational cruises in the Central North Pacific Ocean for the Naval Oceanographic Office (NAVOCEANO). Sea surface temperature was continuously recorded at ten-second intervals along the ship's trackline and logged on data tapes with position and time of observation.

The temperatures were measured with an HP2801 quartz thermometer mounted in an HP2850C container at a depth of 5m on the ship's hull. With a ten-second gate time, a quartz thermometer of this type is designed to have a potential resolution of 10^{-4}°C . The main advantages of this type of thermometer are the stability of the sensor, the extremely high temperature resolution, the digitized presentation of data, and the compatibility with other recording equipment. Its main disadvantages are the difficulty of field calibration and the possibility of instrument failure due to hull vibration while in operation. The addition of the mounting receptacle on the Silas Bent has made the quartz thermometer very useful for SST observations. In this case, temperatures were recorded to the nearest 0.01°C and positions to the nearest 0.1 minute of latitude and longitude. Prior to sending the data tapes to the Naval Postgraduate School, the temperature data was one-minute averaged by a NAVOCEANO so that the tapes arrived with the temperature data at equal time intervals of one minute for analysis.

B. DATA ASSEMBLY

The data were formatted on the magnetic tapes by block area coverage and had to be organized into a useful form for analysis. This was accomplished by a sorting procedure that reordered the data into a time sequential format. Figures 3 and 4 are examples of the raw reordered data trackline position and sea surface temperature profile. With the data in this form, their continuity was checked and data gaps noted for future reference. A total of 38 full or partial days of data at minute intervals were recovered. In the 38 days, three seasons are depicted: winter, spring, and summer. This permitted a cursory evaluation of seasonal differences in temperature variability.

The longest continuous strings of data were selected for the initial analysis. These included two three-day periods: one in the spring of 1976, and the other in the summer of 1977. The first period was from 7 to 10 April 1976 during cruise 343615 of the USNS Silas Bent. The ship steered an average course of 295T and maintained an average speed of 12 knots over the period. The trackline covered was from 23N 161W to 30N 179W, and the observations represented average spring conditions in the Central North Pacific Ocean. The second set of observations to be analyzed were selected to provide a significant seasonal contrast. The second period covered 18-21 July 1977 during cruise 343722 of the Silas Bent. For this set of observations, the ship maintained an average course of 085T and speed of 13 knots. The trackline coverage was from 33N 149E to 36N 170E and represented average summer conditions in the Central North Pacific Ocean.

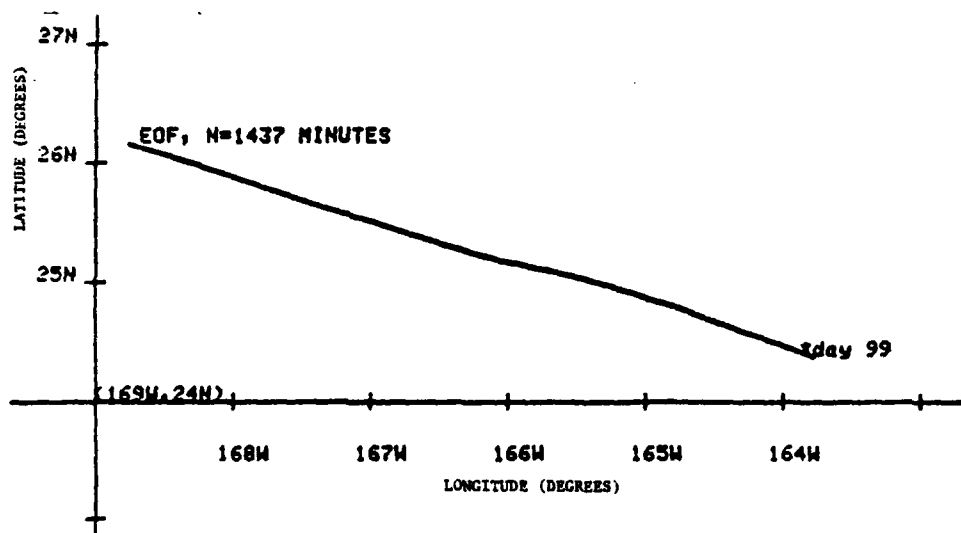


FIGURE 3. Example of trackline position for each minute SST observation for Julian date 99.

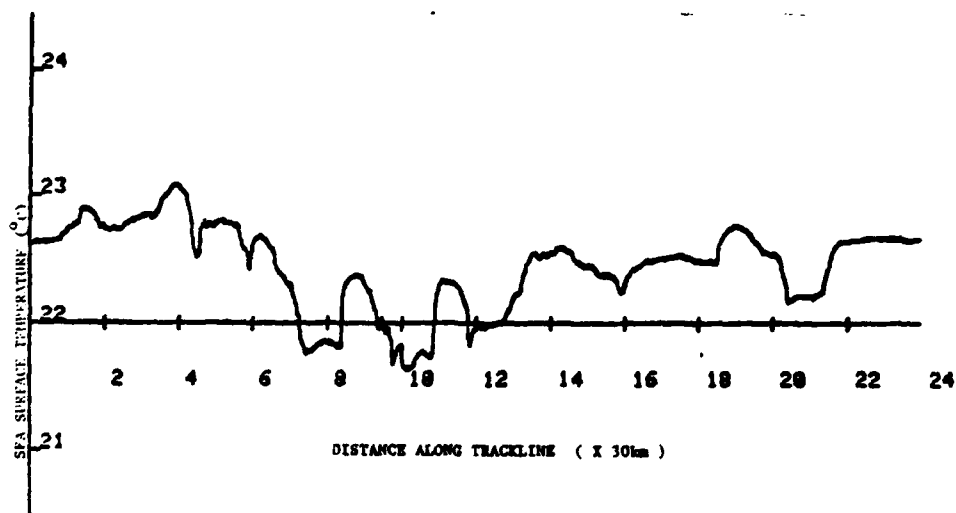


FIGURE 4. Example of daily plot of SST along trackline shown in Figure 3.

The first procedure was to convert the data to an equally spaced format. The conversion to equal spacing is required for statistical analysis in wave number space. The data were converted to 300m intervals by use of a simple linear interpolation scheme for temperature using the logged positions and equal time intervals to determine distances, course, and speed along tracklines, thereby converting digitized temperatures at equal-time intervals into equal-space intervals (Figure 5). No loss of resolution could be detected in the newly digitized data set when compared with the original data. All of the other days of data were handled in this way with data gaps being interpolated individually. In some cases very short records would result in discontinuous pieces of data. In other cases, the ship would stop for an oceanographic station, and the position on the trackline would resume with no spatial gap. In all cases, the times of data voids were accounted for in subsequent time scale analyses of the small scale temperature variability.

C. ATMOSPHERIC DATA

Atmospheric conditions were also obtained for the periods of the SST observations. They were taken from the National Meteorological Center's (NMC) northern hemisphere surface pressure charts, and based on ship reports and computed pressure gradients in the vicinity of the Silas Bent. These charts were available at six hourly intervals for all the days covered by the SST data. The atmospheric variables of interest were pressure, cloud cover and wind velocities. These variables were selected because of possible impact on the SST structure.

The primary deficiency in the meteorological data is that the actual observations from the Silas Bent were not available to NMC. The

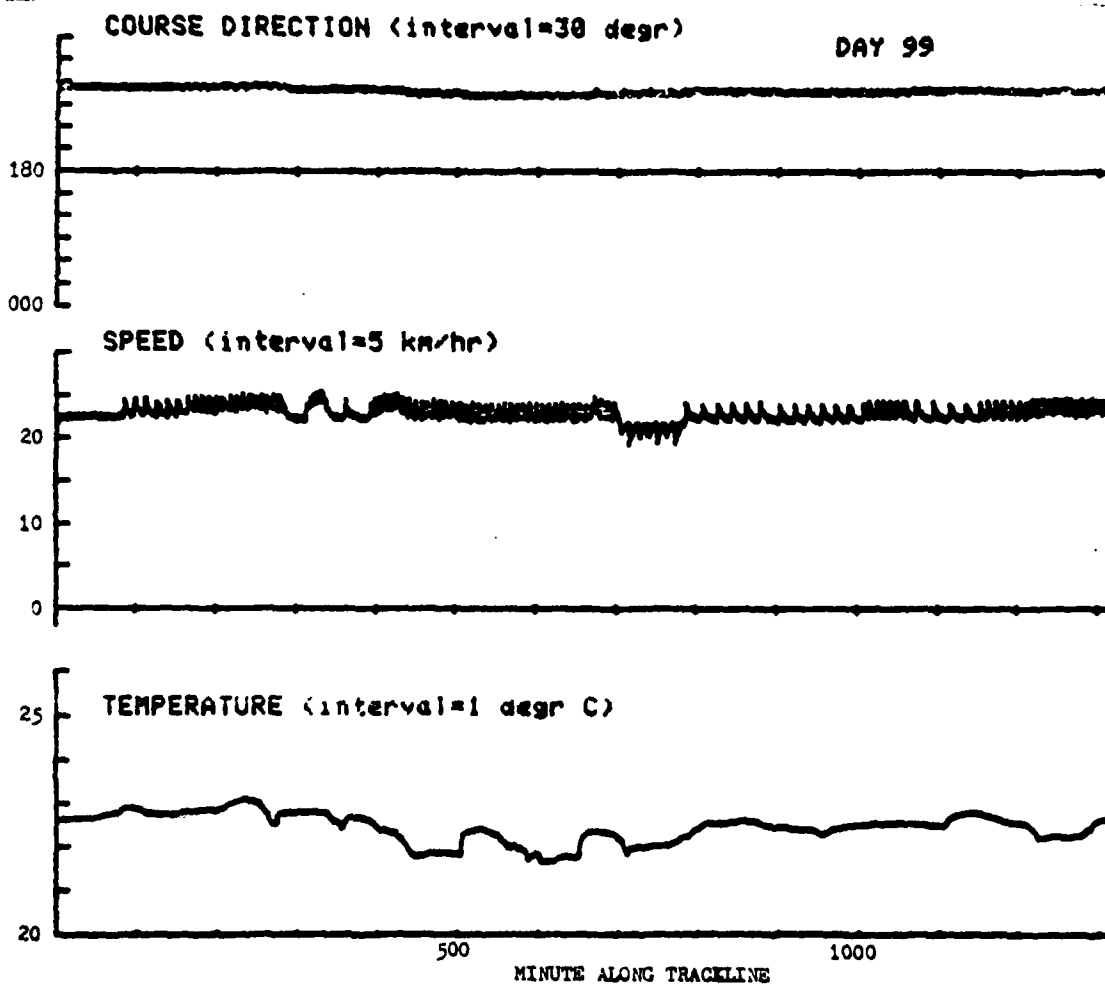


FIGURE 5. Method of linear interpolation from equal time to equal space. Changes in position between each observation were used to compute course, speed, and distance covered in each minute interval. The temperature change was assumed to be linear and the temperature every 300 m. determined.

conditions for the ship location had to be interpolated from available ship reports. Therefore, the atmospheric conditions are only estimates of what the ship was actually experiencing. This deficiency is not believed to be too serious for this initial study.

D. ERRORS IN THE DATA

Possible errors can arise due to the methods used to gather and assemble the data sets. The problem with maintaining the absolute accuracy of the quartz thermometer has already been mentioned. This error is not a problem because only the relative temperature or perturbations from a mean temperature are actually analyzed. There also is some degradation of the data due to converting from equal time to equal space. This should not be significant because the ship usually maintained a steady course and speed. Finally, errors that might be induced in the atmospheric data should have little consequence since the purpose of the study is to look only at general trends in the atmospheric forcing.

III. STATISTICAL ANALYSIS PROCEDURES

A. SPECTRUM ANALYSIS AND DATA FILTERING

Spectral analysis and filtering was performed using the radix 2 fast Fourier transfer (FFT) decimation algorithm of Sande and Tukey [Brigham, 1974]. The algorithm was programed as a library subroutine available in the Tektronics 4052 desk top computer. Using the desk top computer to calculate spectra resulted in the data being handled at a somewhat slower but efficient rate, without the dependence on a main frame computer.

To eliminate large scales of temperature variability that were not being considered by this thesis, a high pass filtering technique was designed for the data. The technique uses Fourier series elimination, [Bath, 1974], to filter out the low frequency temperature variance spectra from the total signal, leaving the higher frequencies to be analyzed. The entire data length of 2048 points, representing about 600km (Figure 6), was high pass filtered to minimize the end effects which result in spectral leakage. The data were demeaned and Fourier analyzed using the FFT algorithm. Fourier coefficients at frequencies greater than the frequencies of interest were then set equal to zero and the resulting Fourier spectrum inverse transformed by the FFT to reform the low pass time series signal comprising the larger scales of temperature variability (Figure 7). The low frequency time series was then subtracted from the total temperature signal (Figure 6) leaving the scales of interest for the analysis (Figure 8).

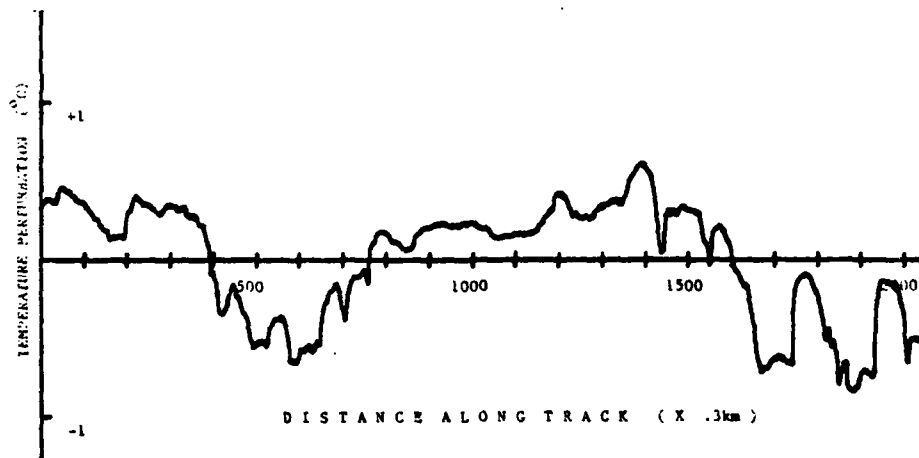


FIGURE 6. Total temperature perturbation along trackline.

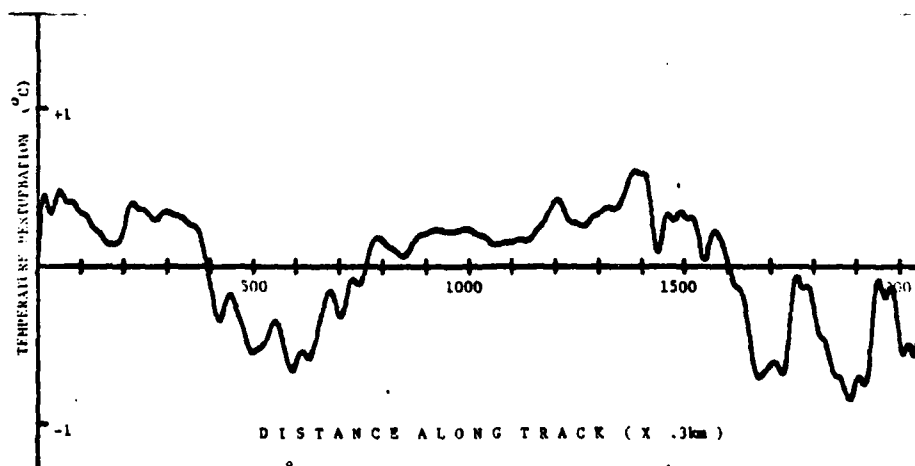


FIGURE 7. Large scale component of temperature perturbation along trackline for Figure 6. (>10 km)

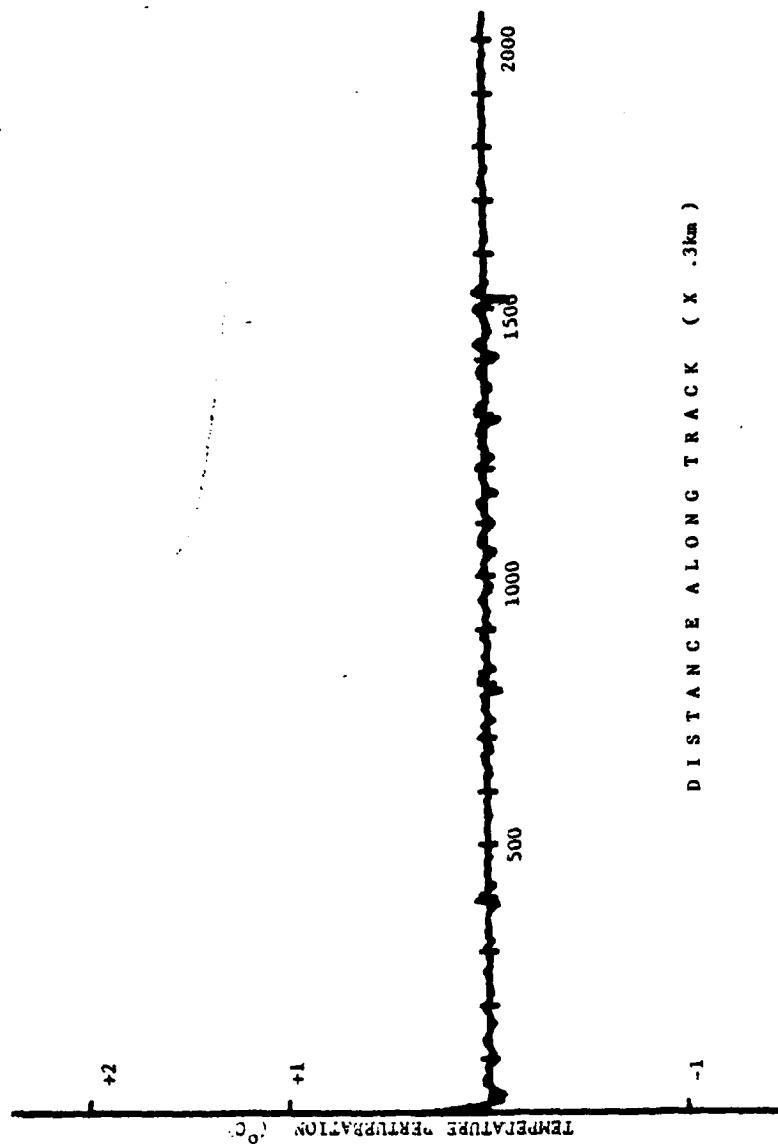


FIGURE 8. Small scale component of temperature perturbation along trackline in Figure 6. (<10 km)

The scales of interest for the study were determined by experimenting with the data sets and observing how the variability seemed to change at different spatial scales. Since the small scale variability was of interest, scales of 76.8km and less were initially chosen representing a filter cut-off at $.08 \text{ km}^{-1}$. When smaller scales were to be analyzed, the filter cut-off was increased to 0.62 km^{-1} corresponding to a wave length of 10km.

For tracks of data with less than 2048 points, a similar method of filtering was used to eliminate the large scale variability based on Fourier coefficients for either 512 or 1024 data points. Filtering the data is designed to exclude large scale variability and reduce spectral leakage from end effects without inducing errors in the small scale temperature patchiness patterns.

B. SPECTRAL ESTIMATES AND ENSEMBLE AVERAGING

Having filtered out the low frequency components of the temperature variance, the modified data was initially divided into eight 256-point segments, covering scales up to 76.8km, for input into the FFT. The FFT algorithm was used to calculate raw, one-sided power spectra of temperature variance density on each segment as given by equation 2,

$$E_T(k) = \frac{2(a_k^2 + b_k^2)}{\Delta k} \quad (2)$$

where $E_T(k)$ is the power spectral estimate for temperature variance density in units of $C^2\text{-km}$ at wave number k in cycles /km, (km^{-1}) . The Fourier coefficients a_k and b_k are obtained from the FFT for a particular wave number k . The resolution Δk of the spectra in wave number space

equals $2\pi/N\Delta x$, where N is the number of data points used and Δx is the 300m spacing between data points. The highest wave number that can be resolved is based on the Nyquist frequency and equals $\pi/\Delta X$ or about 10.5 k^{-1} for the data set.

The raw spectral estimates were ensemble averaged to increase the statistical stability in the spectral results. Assuming that the temperature is a random process with a Gaussian distribution, the chi-square distribution can be used to form confidence limits on the spectral estimates. Each raw spectral estimate contributes two degrees of freedom to the average spectral value of the process. Ensemble averaging of eight spectra results in each spectral estimate having 16 degrees of freedom since the degrees of freedom are additive. By ensemble averaging, the statistical stability of each spectral estimate is improved and the confidence interval becomes narrower. Ninety-five percent confidence limits, based on the degrees of freedom in each spectra, have been used exclusively in this study and are plotted on most spectra. Examples of average spectra, covering two three-day periods, with 48 degrees of freedom are depicted in Figures 9 and 10. Seasonal and daily variations in temperature variance are examined by comparing averaged spectra.

C. PROCESSING INITIAL TEST SPECTRA: 0.6 TO 76.8km

Having designed the method to be used for determining spectra, the two data sets selected for initial study could now be processed. Both records spanned three days during which time approximately constant ship course and speed were maintained, with no significant (greater than 10 minutes) gaps in the SST record.

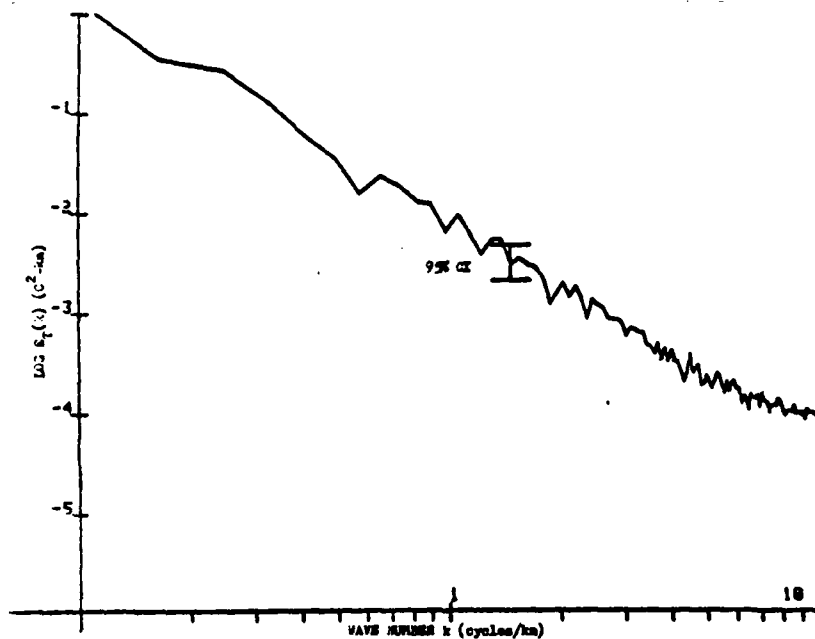


FIGURE 9. Average temperature variance spectrum: Spring. Spectrum is based on three days of data. Confidence limits are based on 48 degrees of freedom and a chi-square distribution.

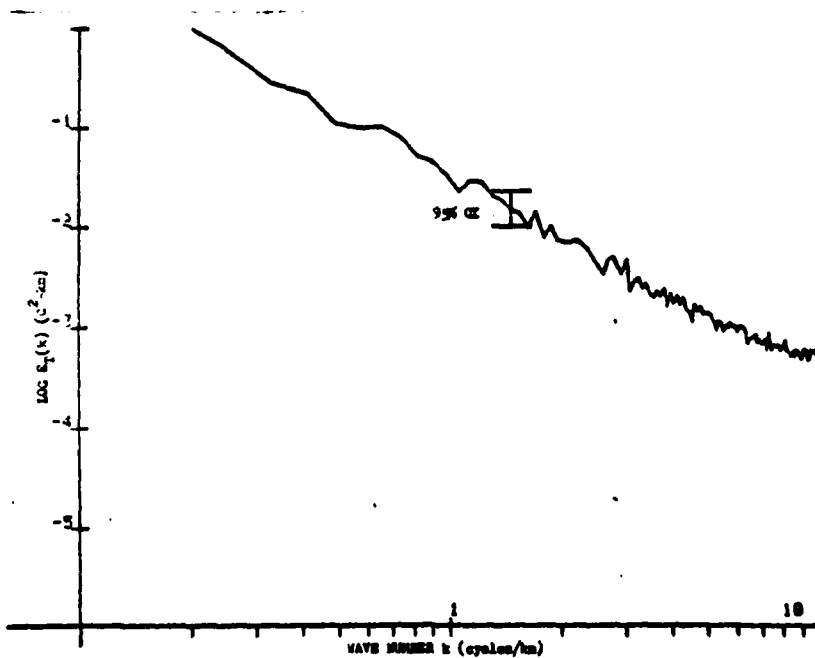


FIGURE 10. Average temperature variance spectrum: Summer. Spectrum is based on three days of data. Confidence limits are based on 48 degrees of freedom and a chi-square distribution.

Each three-day data record was split into three 614.4 km sections of 1048 SST values. Contributions to the temperature variance on scales greater than 87.7km were eliminated from each record using the high pass filter. These modified records were then split into eight sections of 256 points. Temperature variance spectra were then computed for these sections, providing spectral density information on length scales between 0.6 and 76.8km or wave numbers between 10.5 and 0.08 km^{-1} . A representative set of these individual spectra (Figure 11) are plotted as the log of temperature variance versus the log of wave number so that if a power law relationship exists according to eq.(1), it will plot as a straight line. The vertical bars are the 95% chi-square confidence intervals based on the degrees of freedom in each spectrum. The confidence interval is wide since these spectra are based on only two degrees of freedom. The last spectrum on the figure (case 9) is the averaged spectrum for the previous collection of eight spectra shown, giving it 16 degrees of freedom. It therefore is a more stable statistical representation of the typical temperature variance structure on an approximately one-day average.

The average spectra for each three-day period in the initial data set were computed in a similar manner and plotted (Figures 9 and 10) based on 48 degrees of freedom. The initial study of temperature variance structure was based on the analysis of Figure 9 and 10 and individual spectral depiction as shown in Figure 11. The results to be derived from the data are the general characteristics of the temperature variance spectra, including its slope, magnitude, and how it changes daily and seasonally. These results can then be compared with atmospheric conditions at the time of the observations. Atmospheric conditions for

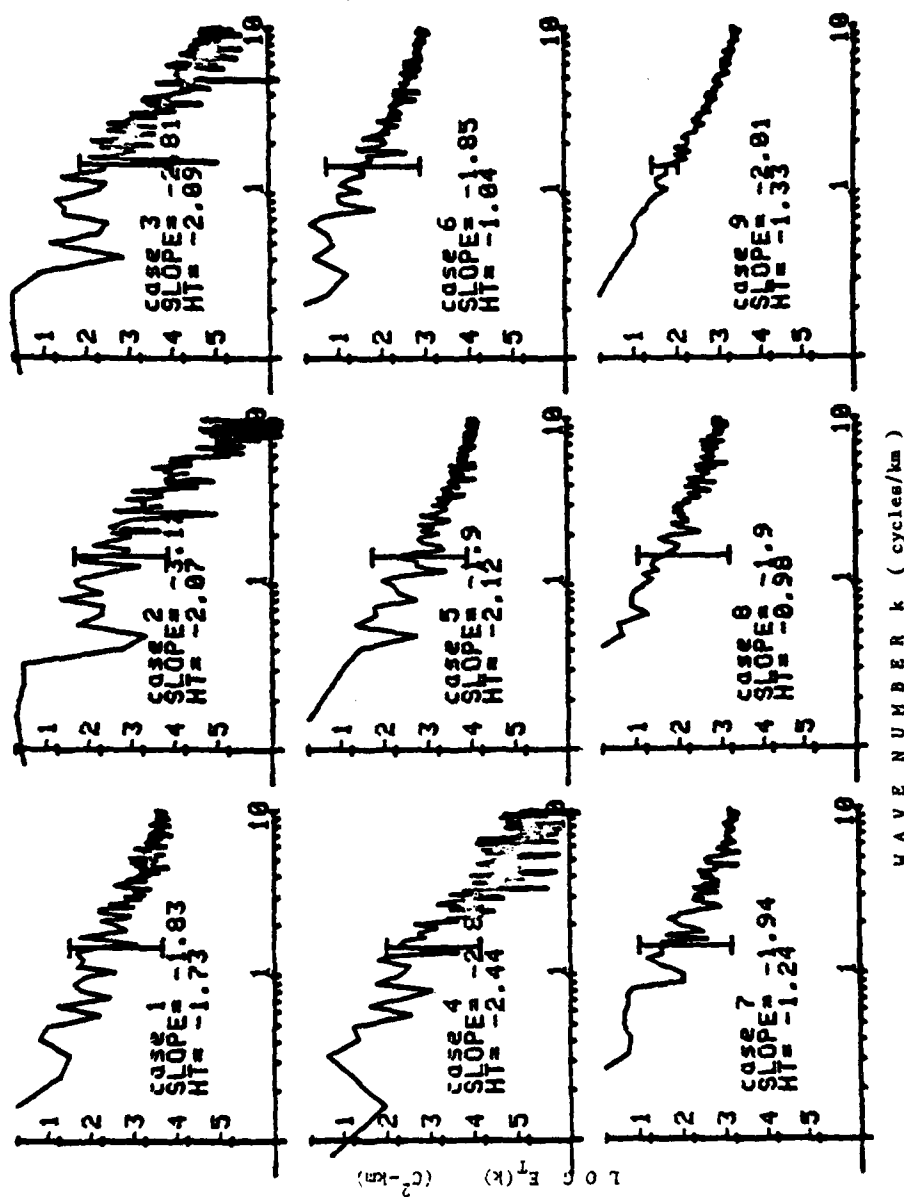


FIGURE 11. Four-hour temperature spectra with two degrees of freedom. Each spectrum is based on 76.8 km of data covered in four hours. The slope value is based on a least square fit of the data. The "HT" is the least square value of the log of variance at $k=1$. Cases are in consecutive order except for case nine which is the average of the preceding eight spectrum. All confidence interval are for 95% based on a chi-square distribution.

the ensemble averaged spectra were determined by averaging wind and cloud conditions for the same periods included in the spectra. The changes in average atmospheric conditions were then compared with changes in temperature variance in order to test and refine the working hypothesis. These results were used to design the final processing method for the rest of the data.

D. FINAL SPECTRA PROCESSING: 0.64 to 9.6km

Based on the preliminary analysis it was decided to refine the analysis procedure to focus attention on the shorter spatial scales. This would then permit the examination of changes in SST patchiness on time scales of several hours, and any diurnal cycle in horizontal temperature variance could be resolved. The remaining shorter sections of data were also included by use of a modified high pass filter. Variance on scales greater than 10km was removed from all input data sets. The modified data sets were further divided into segments of 32 data points, which in turn were transformed into temperature variance spectra representing scales 0.64 to 9.6km, or wave numbers from 0.65 km^{-1} to 9.8 km^{-1} . Spectra with 16 degrees of freedom for each spectral estimate were computed for each group of 256 data points as shown in Figure 12. This figure shows temperature variance for the same time period and trackline as Figure 11, but with greater statistical stability, enabling a more reliable comparison with local apparent solar time and changing atmospheric conditions. One difficulty encountered in the final processing was the large number of gaps in the temperature data that prohibited complete diurnal coverage for most days. As a result, day to day comparisons of temperature variance were frequently limited to fractions of complete days.

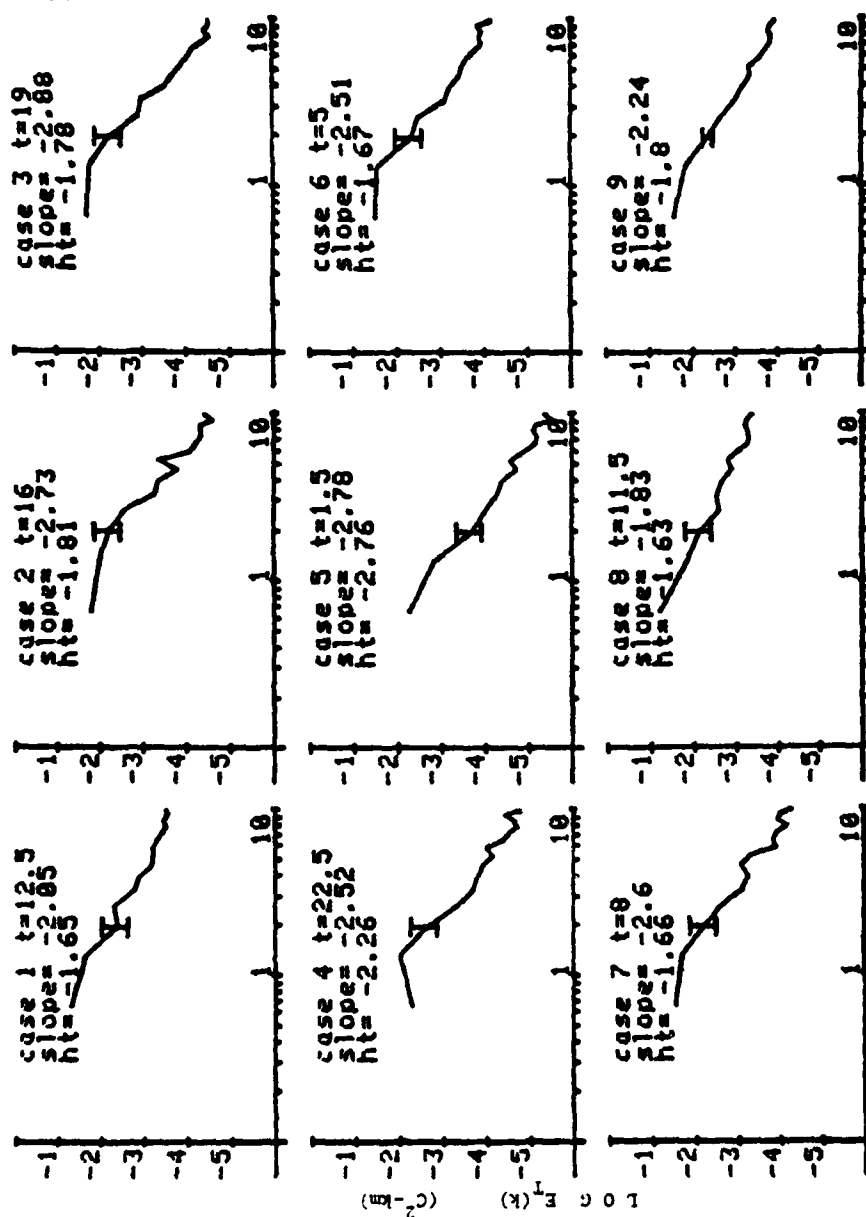


FIGURE 12. Four-hour temperature spectra with 16 degrees of freedom. Each spectrum is based on the same area covered in Figure 11, but is an average of eight spectra from 9.6 km segments over the area. Other information is the same as Figure eleven. "t" is the average time of the spectral depiction.

IV. DISCUSSION OF RESULTS

A. GENERAL STRUCTURE OF PATCHINESS

The general structure and magnitude of the temperature variance is seen by examining the average spectra derived from the data sets. The results of this study show many of the same characteristics of the general SST patchiness structure previously determined in experiments. There is a continuous decrease in temperature variance spectra with increasing wave number, similar to the cascade of energy down to smaller turbulence scales as theorized by Batchelor [1959]. The slope of the fall off on a log scale fit to eq.(1) was determined from a least square fit of the spectral estimates. The fall off slopes for this study ranged from -1.5 to -2.5, which are in agreement with the results of Deschamps, et al, [1981]. Figures 9 and 10 are representative average spectra from two different seasons included in the data set. The slopes of the two spectra are -2.09 and -1.95 respectively, which compare very well with the results of Fieux, et al, [1978] and Saunders, [1972]. Figures 11 and 12 are similar and show more structure, but with larger confidence intervals due to fewer degrees of freedom. In general, these results seem to indicate that the shape and magnitude of the spectra are comparable to the results of earlier studies.

One important difference in this data is the lack of a significant flattening of the spectrum at wave numbers greater than three km^{-1} . There is a definite indication in Figures 9 and 10 that the spectra do have a slope change in this region, however. It was hoped that the

final analysis, concentrating on scales less than 10km, would permit a closer scrutiny of this feature.

As seen in this study and in previous studies, there is no equilibrium theory that explains the variety of slopes found for the measured spectra. The probable explanation for these differences may be revealed by the following sections which show how the temperature variance changes on a relatively short time scale. The power law fall off at a constant rate proposed by most theoretical studies of turbulence phenomena is therefore not a constant, but varies with the changing structure of the patchiness. In other words $p=p(k,t)$ in eq.(1).

B. SEASONAL VARIABILITY IN TEMPERATURE VARIANCE

The seasonal variability in SST variance was examined by comparing spectra from different seasons of the year. The results are shown in Figures 13 and 14. In Figure 13, the average three-day spectra from the spring (Figure 9) and summer (Figure 10), are plotted on the same set of axes with 95% confidence intervals based on 48 degrees of freedom. The magnitude of the temperature variance for summer conditions is greater than spring conditions by almost one order of magnitude for all wave numbers considered. These spectra only cover two representative three-day periods of data. However, Figure 14 shows the least square fit value for all of the average daily spectra at wave number one (6.3km) plotted against day of the year. The straight line on the figure is a least square fit. Again, an order of magnitude increase in the average temperature variance can be seen in going from average winter to average summer conditions.

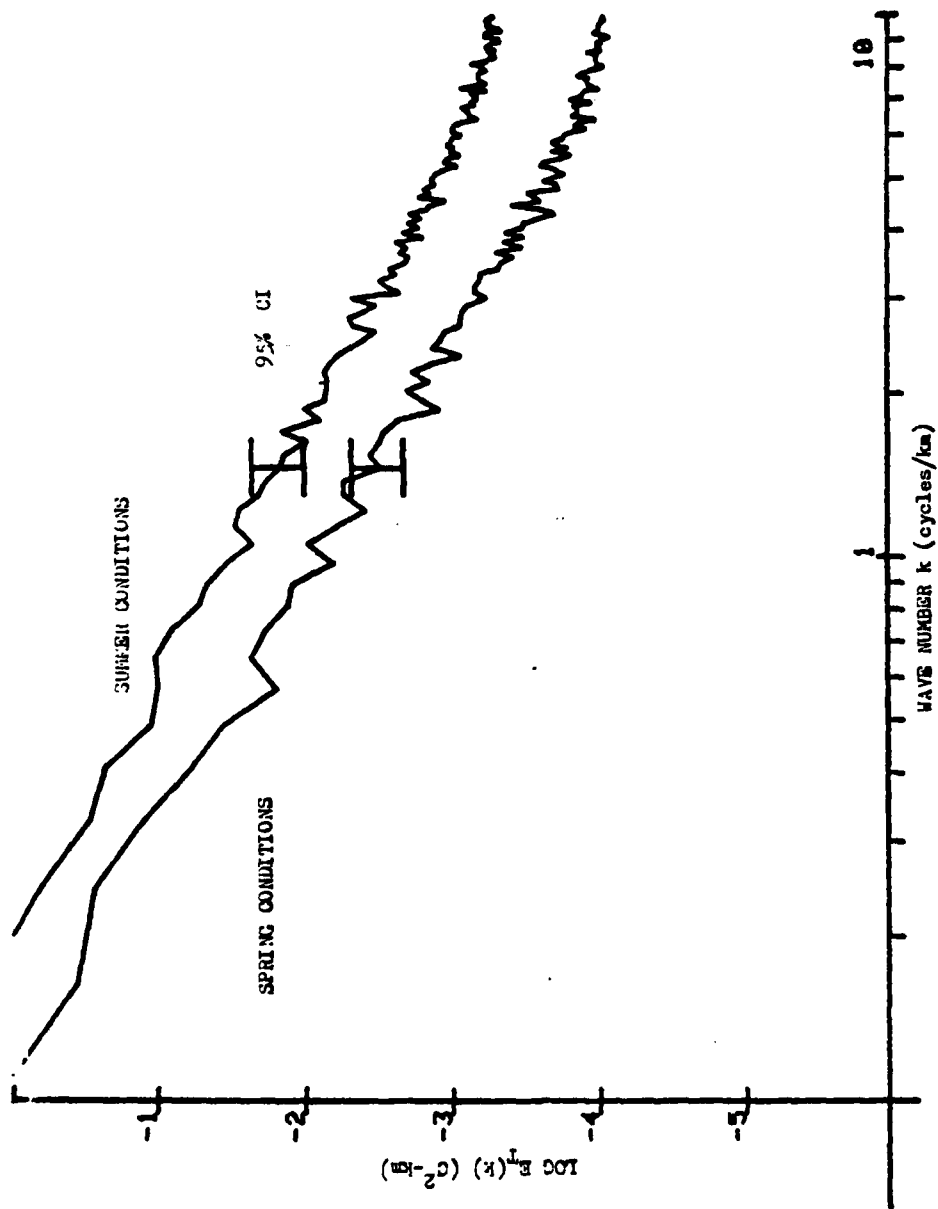


FIGURE 13. Comparison of average summer and spring spectra.

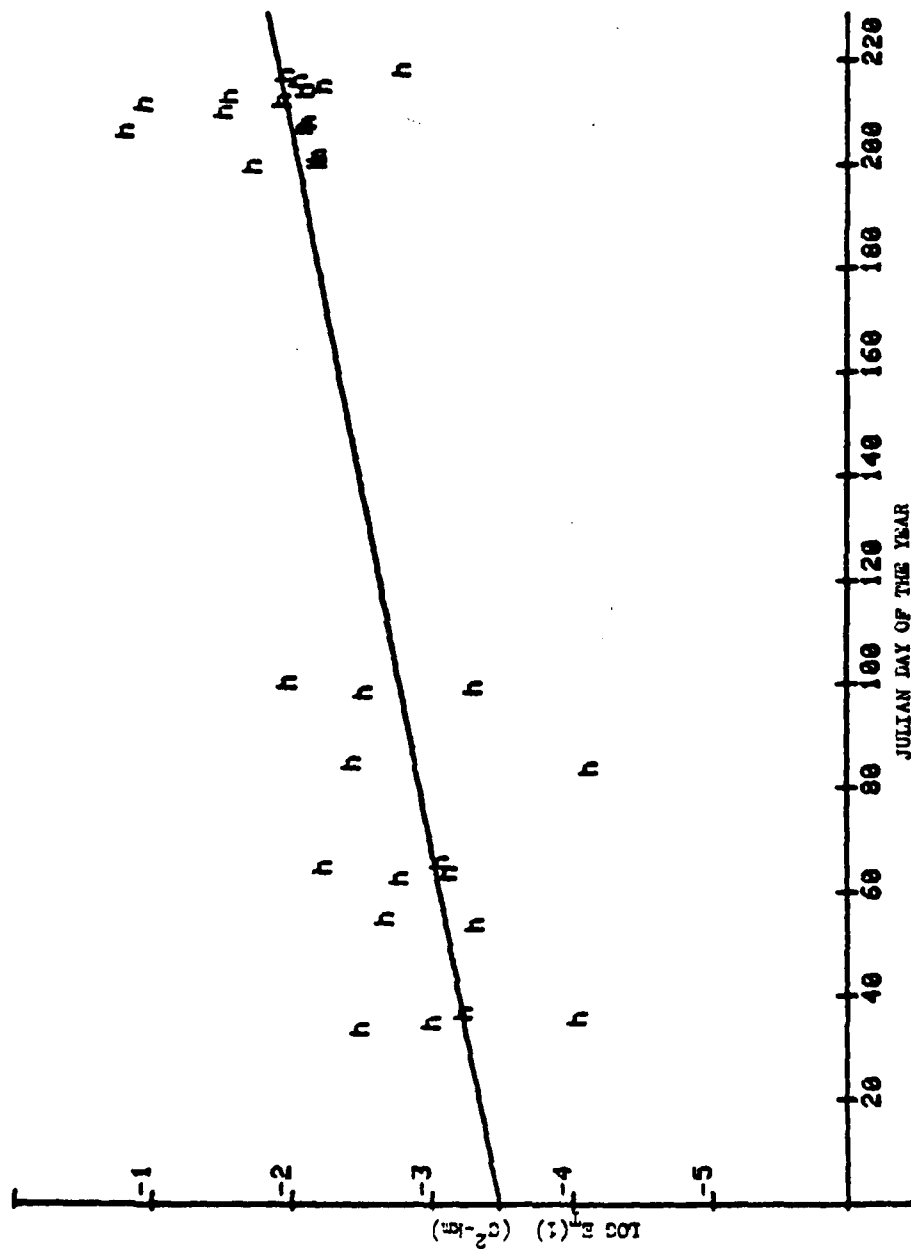


FIGURE 14. Average daily temperature variance at $k=1 \text{ km}^{-1}$ for each day of data. The straight line is a least square fit for the plotted data and shows the increase in temperature variance from winter to summer.

Based on the hypothesis that atmospheric forcing has a direct influence on the patchiness structure, this result is not surprising. Generally, there is more mechanical mixing and possible convective mixing due to synoptic scale storms taking place during the winter and spring seasons, which in turn may reduce the intensity of horizontal patchiness. To rigorously verify this result, more observations from all seasons are needed and the above analysis repeated.

The average slope of the variance structure also changes from season to season, Figure 15. Although at least square fit of these data only show a minor decrease in slope from winter to summer, this result can be explained by an increase in variance at small spatial scales during the summer, and is consistent with the influence of seasonal atmospheric conditions on the patchiness structure. This finding of greater seasonal variability in temperature variance on the smaller spatial scales may help explain the differences in slope values reported in previous studies.

C. DAY-TO-DAY VARIABILITY IN TEMPERATURE VARIANCE

Daily changes in SST variance are determined by comparing time series of spectral estimates for the same wave number in each spectra. Representative variability in temperature variance on this time scale are shown in Figures 16 and 17 for spring and summer conditions, respectively. These graphs show how the variance changes within each day and between different days as represented by the various curves. The magnitude fluctuates from one day to the next by as much as two orders of magnitude, Figures 16 and 17.

Figures 18 and 19 cover the same periods of time but show spectral values for wave number 9.8 km^{-1} (0.64 km). Note that although the magnitude

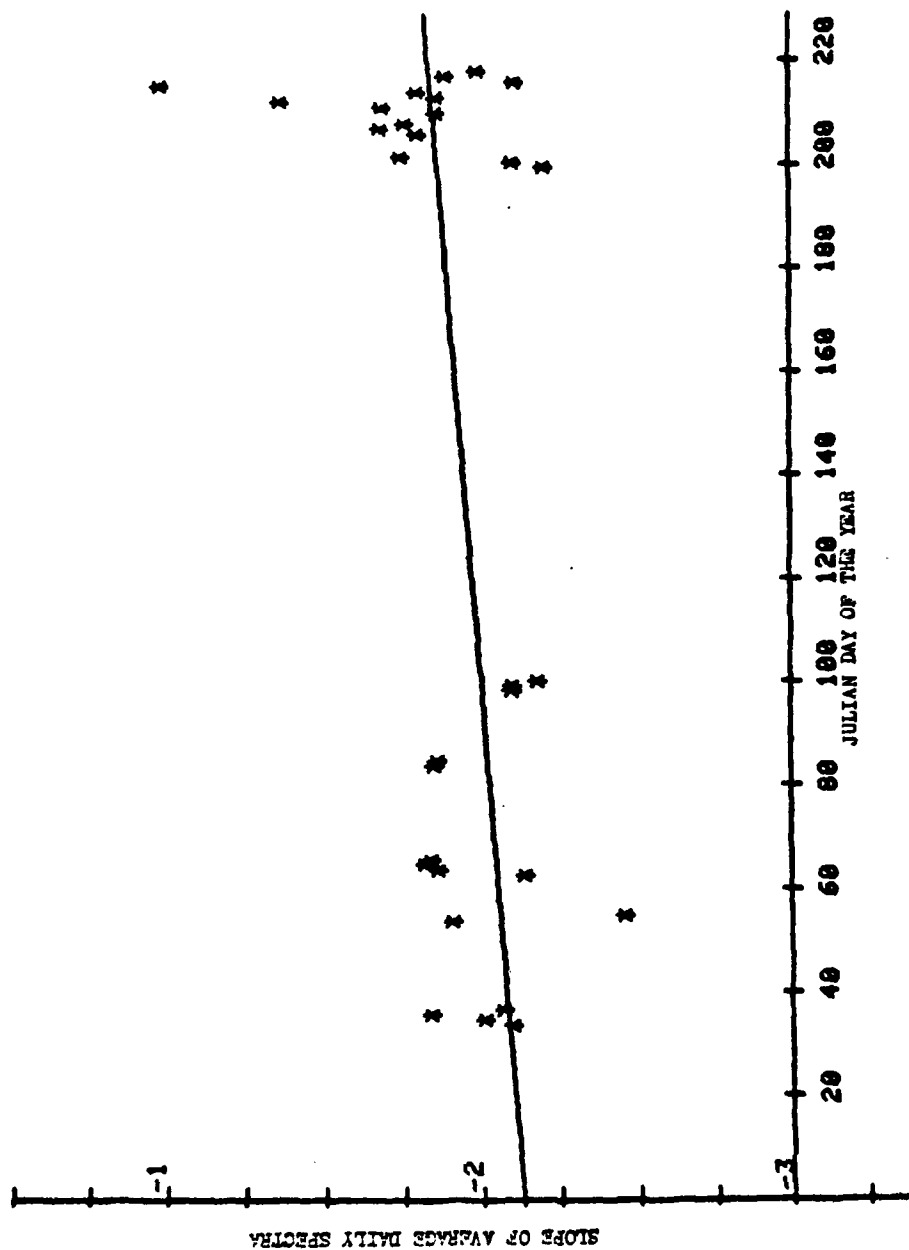


FIGURE 15. Spectral slope for average daily spectra for each day of data based on a least square fit. The straight line is a least square fit for the plotted data.

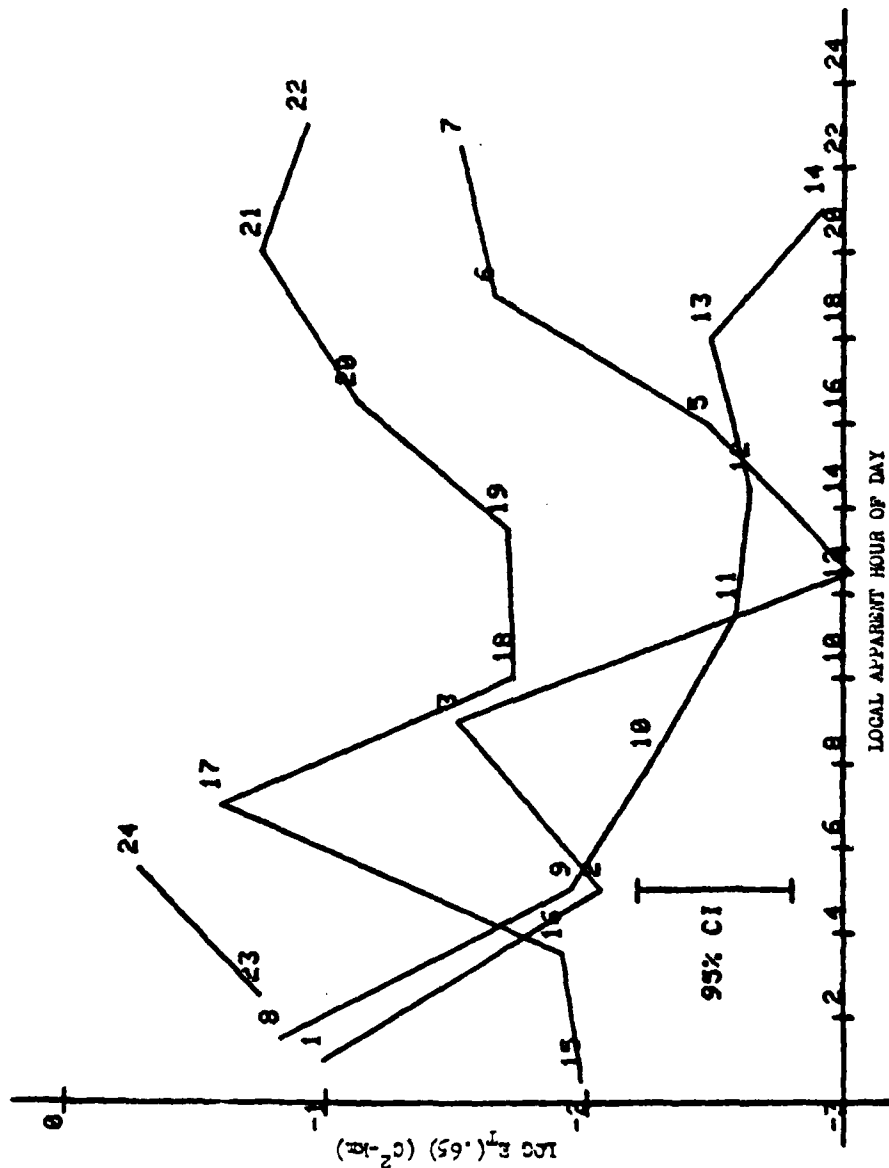


FIGURE 16. Diurnal variation in SST spectra for wave number $k = 0.65 \text{ km}^{-1}$: spring conditions. The numbers on the plot indicate the sequencing of consecutive spectra in time.

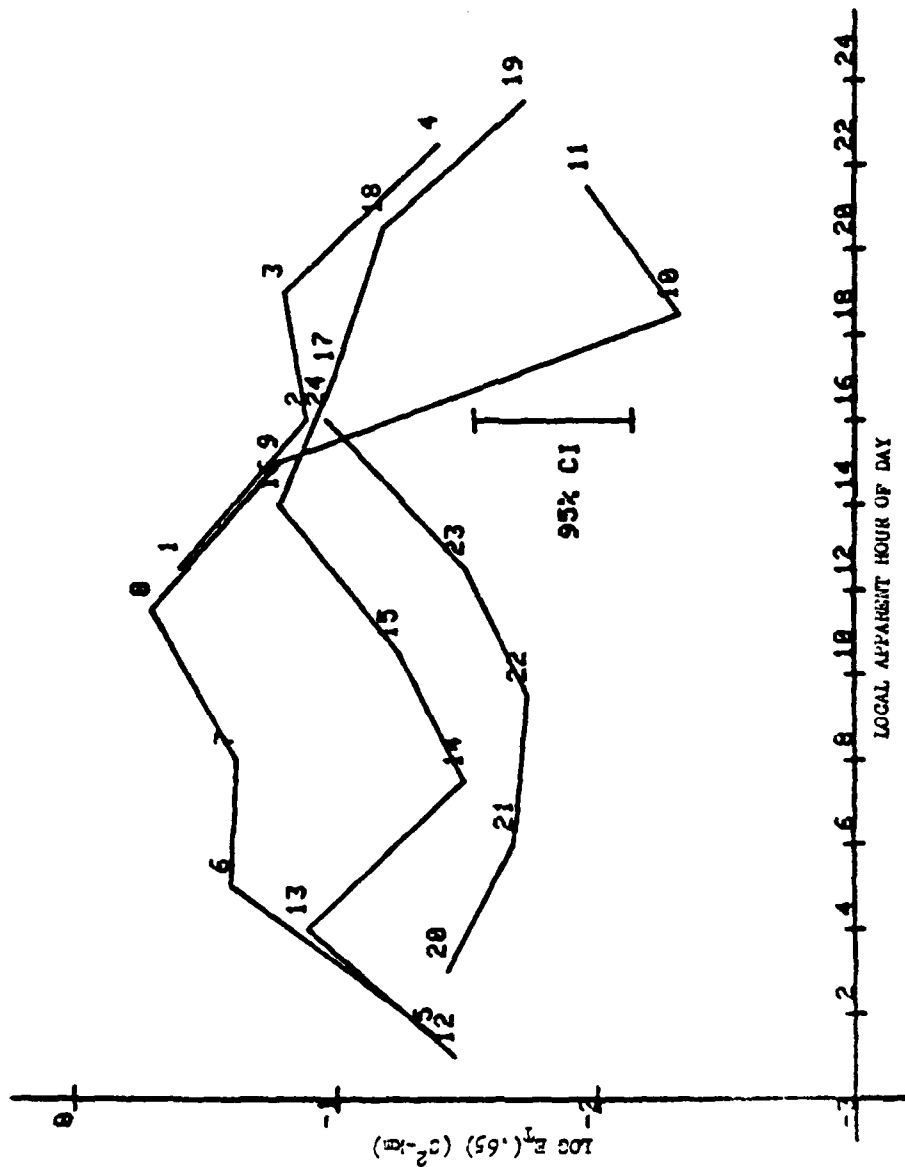


FIGURE 17. Diurnal variation in SST spectra for wave number $k = .65 \text{ km}^{-1}$; summer conditions. The numbers on the plot indicate the sequences of consecutive spectra in time.

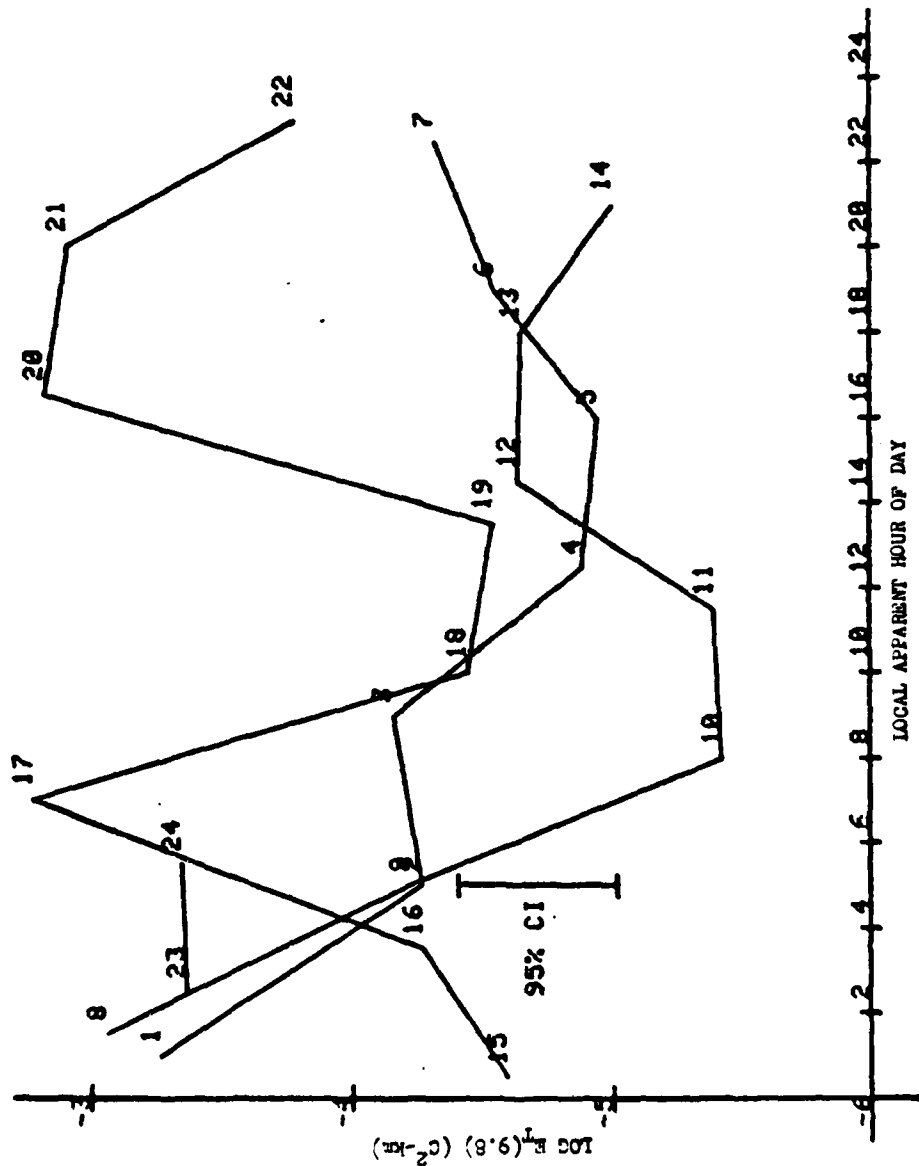


FIGURE 18. Diurnal variation in SST spectra for wave number $k=9.8 \text{ km}^{-1}$: spring conditions. Numbers on plot same as Fig. 16.

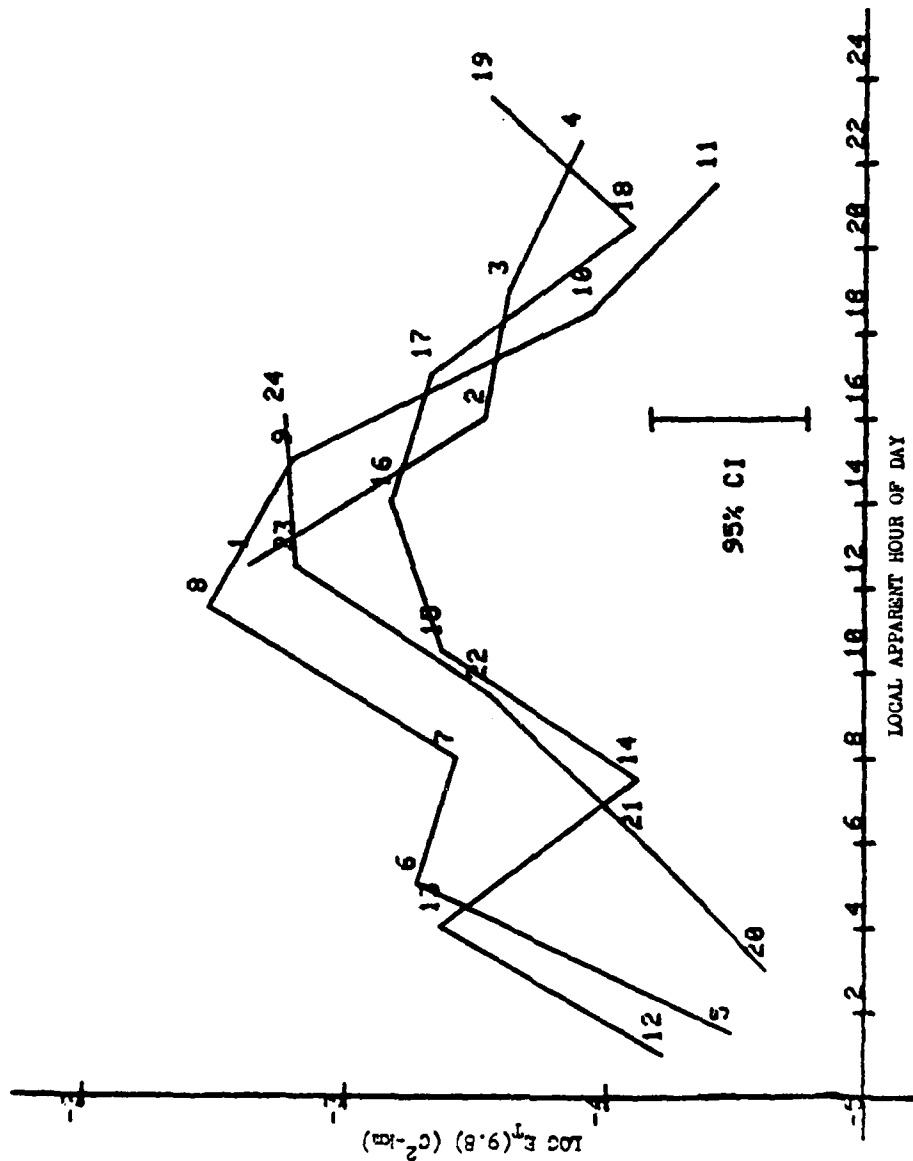


FIGURE 19. Diurnal variation in SST spectra for wave number $k=9.8 \text{ km}^{-1}$; summer conditions. Numbers on plot same as Fig. 17.

of the temperature variance has fallen off with the increase in wave number from 0.65 to 9.8 km^{-1} , the general shape of the day-to-day variability has not markedly changed with increasing wave number. This is interpreted as an indication that whatever is causing the change in temperature variance is having similar effects at all wave numbers in the limited range studied.

All of the day-to-day plots of spectra exhibited similar variability on what may correspond to the atmospheric synoptic scale. A possible explanation for these fluctuations may therefore be changes in atmospheric forcing over the sea surface. Based on the meteorological data available, day-to-day changes in cloud cover and wind speed were correlated with the day-to-day changes in temperature variance. The changes in the daily spectral value at wave number one was chosen as a representative measure of the variation in the total temperature spectra. Day-to-day changes in temperature variance are shown in Figures 20 - 23. The plots are similar to Figure 14 with consecutive points connected. The symbols represent the average daily changes in the atmospheric variables (wind speed/cloud cover) being correlated. The figures show how the atmospheric conditions were changing compared with changes in the temperature variance. Figures 20 and 21 show the visual correlation with wind conditions, and Figures 22 and 23 with cloud cover for each day in the data set.

The effects of wind changes are most obvious. Decreasing winds correlate with increasing variance and increasing winds correlate with decreasing variance in almost every case examined. The changes in cloud

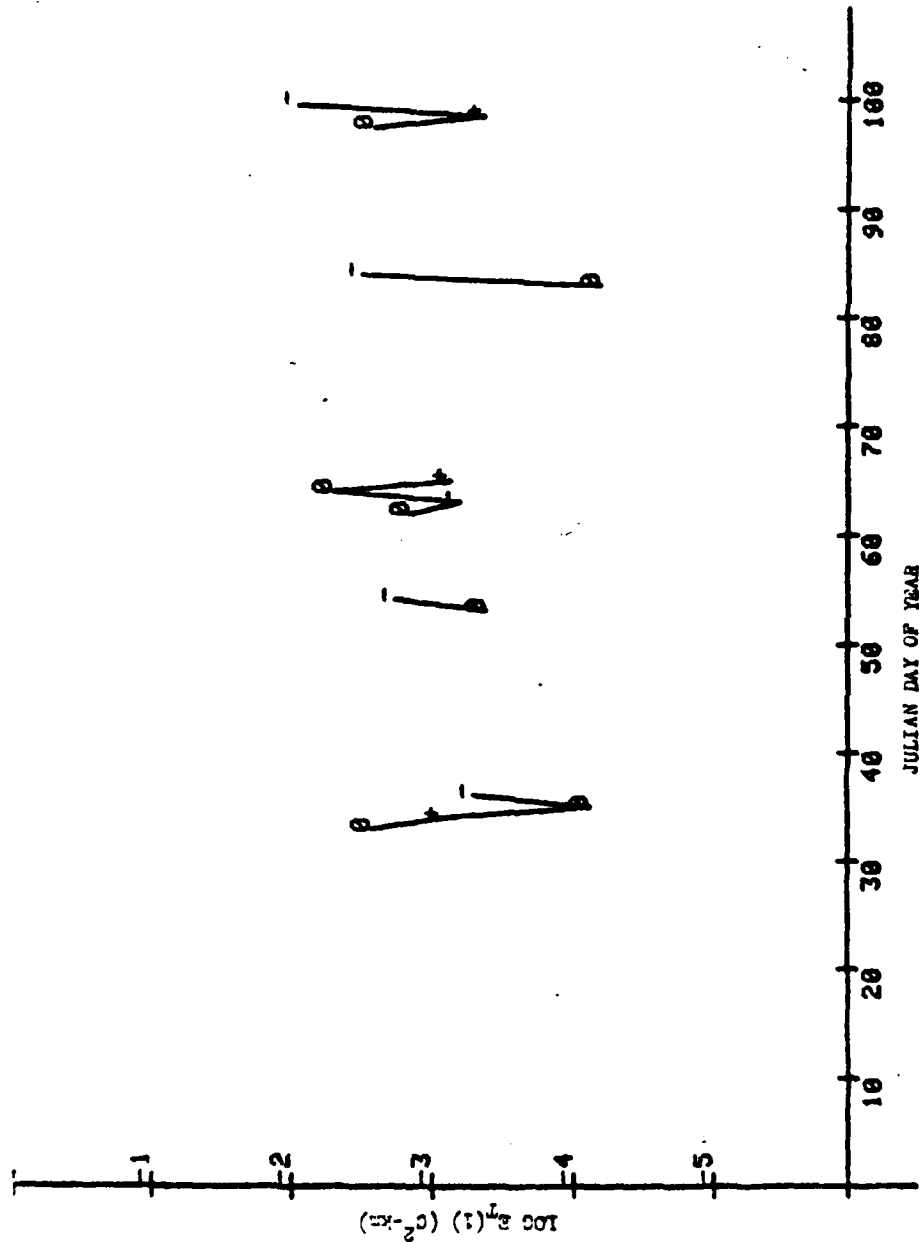


FIGURE 20. Correlation between changing temperature variance and changing wind speed: Julian days 1-100. The lines show the daily change in variance. The symbols represent daily changes in wind speed. A "O" means initial conditions or no change. A "+" means an increase in wind speed. A "-" means a decrease in wind speed. All changes are from one day to the next based on average daily conditions for wind and variance.

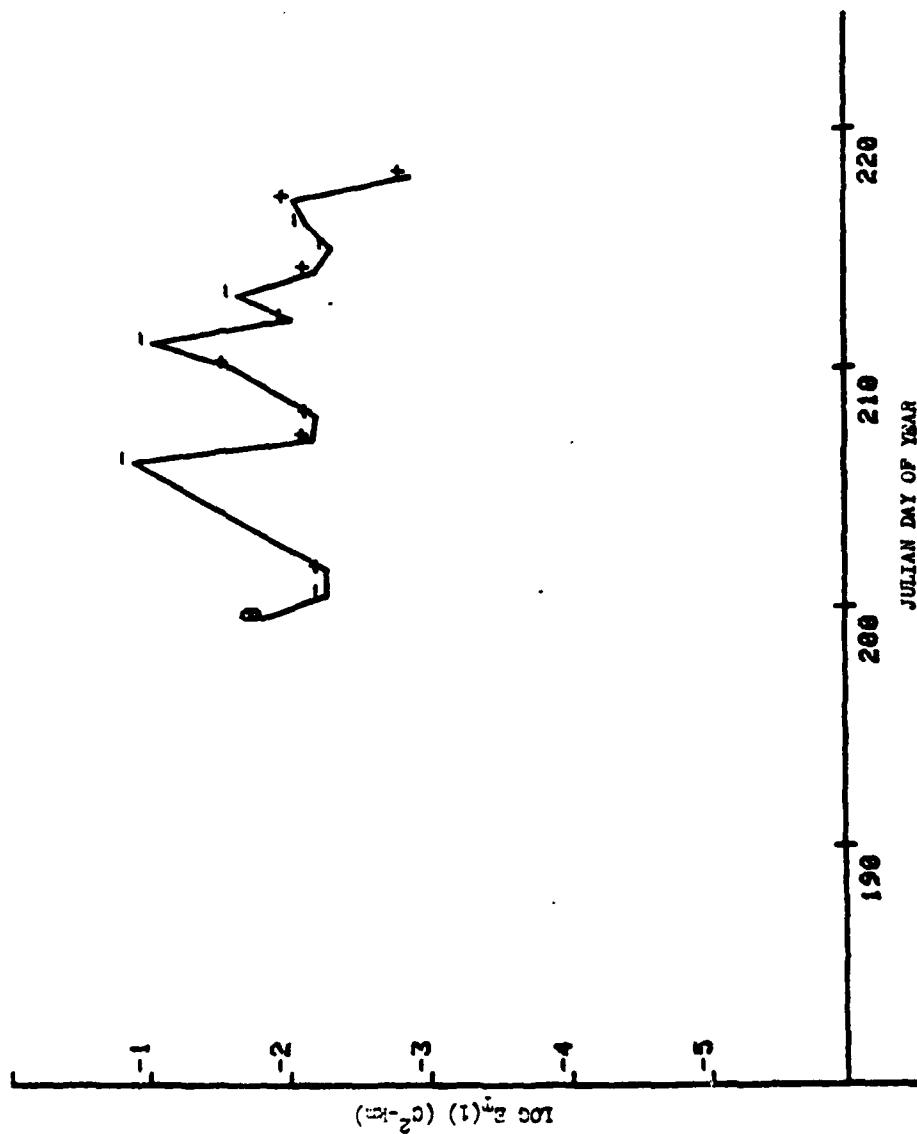


FIGURE 21. Correlation between changing temperature variance and changing wind speed: Julian days 180-230. Symbols are the same as Figure 20.

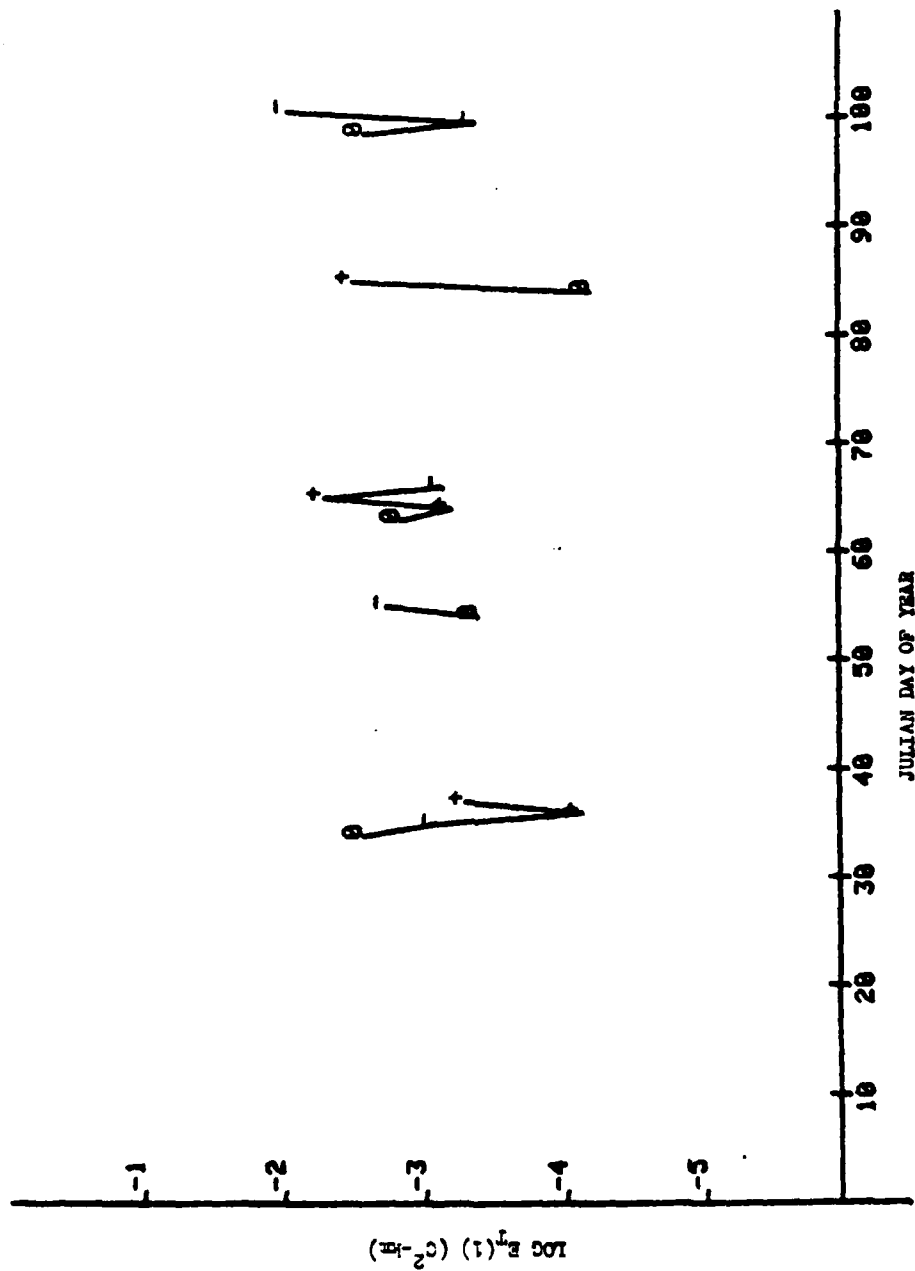


FIGURE 22. Correlation between changing temperature variance and changing cloud cover: Julian days 1-100. The symbols are similar to Figure 20 except for cloud cover changes.

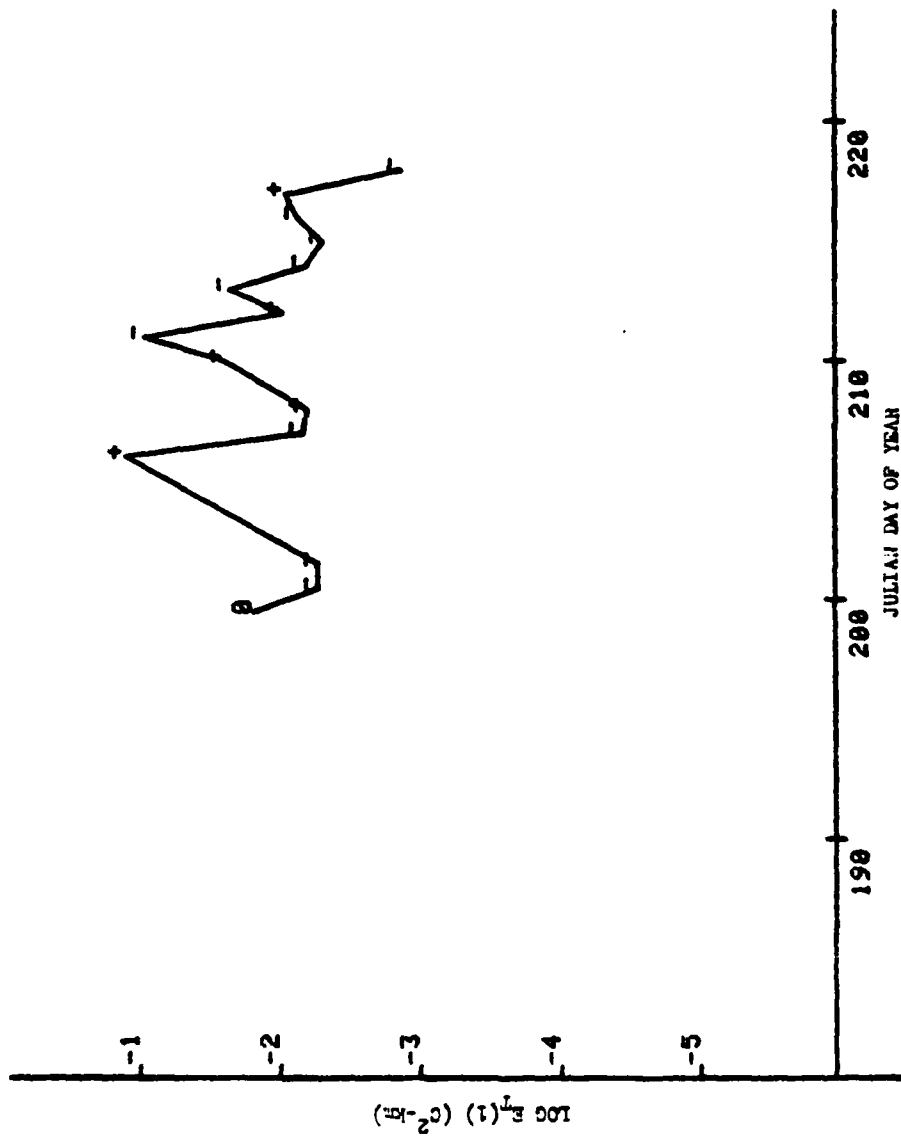


FIGURE 23. Correlation between changing temperature variance and changing cloud cover: Julian days 180-230. Symbols are the same as Figure 22.

cover do not seem to correlate well with the changes in variance for any time of year. It is thought that the wind correlation is quite significant and is a strong initial verification of the general hypothesis.

D. DIURNAL VARIABILITY IN TEMPERATURE VARIANCE

In addition to the day-to-day changes in temperature variance spectra (Figures 16 - 19), there are diurnal or 24-hour changes in the temperature variance structure. Similar diurnal variations in SST spectra were previously reported by Moen [1973]. These diurnal changes can be as large as two orders of magnitude. The spectral magnitudes appear to depend on the local apparent time of day, suggesting that the diurnal heating cycle may be the cause.

The general structure of the daily change shown in Figures 16 - 19 is very representative of the diurnal changes seen in the rest of the data analyzed in this study. The patterns seem to indicate a cycling of the variance spectra throughout the day, with some days possibly having a semi-diurnal response. There also seems to be a wave number dependence in the diurnal cycle because larger wave numbers have more variability as seen in comparing Figures 16 with 18 or 17 with 19. The change in magnitude of the variance from spectrum to spectrum within a day also is reflected in a slope change in the log-log spectral plot. The variability in slope caused by large diurnal fluctuations at smaller spatial scales may help explain why theoretical studies of the temperature variance structure differ from observed results. Attempts were made to compare changes in hourly variance spectra with atmospheric conditions, similar to the day-to-day changes. However, the meteorological data

could not be resolved sufficiently accurately in time to permit any conclusions more specific than the observation that wind changes do affect the diurnal variance cycle. More atmospheric data are needed to gain an insight into what is causing the diurnal variation in the patchiness structure. It is assumed that solar radiational fluxes, cloud cover and wind speed changes could probably be related to the changes in temperature variance if better observations were available.

V. CONCLUSIONS AND RECOMMENDATIONS

Thirty-eight different days of horizontal surface temperature variability structure were examined by comparing changes in variance spectra on different time and space scales with changes in atmospheric conditions. The hypothesis set forth was that atmospheric forcing induces changes in the temperature variability structure. The results showed that the temperature variance spectra change by one-to-two orders of magnitude on seasonal, synoptic, and diurnal time scales. The seasonal and synoptic changes in variance were correlated with changes in the atmospheric mixing processes (i.e., wind conditions) at the air-sea interface and thus seemed to verify the initial hypothesis. The diurnal changes in temperature variance seemed to be associated with time of day and changing atmospheric conditions but only tendencies were observed and no conclusions made since other types of forcing, such as internal waves [Garret and Munk, 1975], may also be influencing diurnal changes in the temperature patterns.

Turbulence theory does not seem to explain the spectral shape as was pointed out by other studies. The results from this study do agree with most previously presented works, but investigate further the variability of the patchiness structure on scales less than 10 km. The temporal variability in patchiness structure may explain why the theories do not explain earlier observational results. Also, the assumption of similarity between turbulent kinetic energy and thermal spectra may be questionable.

One method of future study of this phenomenon will include an examination of the terms of the budget for temperature variance which can be derived from the flux form of the heat equation. Limitations in the meteorological data prevented a careful analysis of this budget. Through such an equation, however, a parameterization scheme for the change in patchiness structure may possibly be derived and tested under various atmospheric conditions. Gradient production of variance, diffusion of variance and surface heat flux production/damping are three terms in the equation that can be directly related to the effects of atmospheric forcing. In this way, a more systematic approach to predicting higher order statistics of the sea surface temperature patchiness structure may be at hand now that the importance of atmospheric forcing has been demonstrated.

Another possible experiment would be the design of a method for measuring SST patterns repeatedly over the same trackline to find how one specific region changes under different atmospheric conditions, thus eliminating any geographic bias in the data. The possibility that SST patchiness is non-Gaussian should also be examined.

In conclusion, changes in atmospheric conditions on seasonal, synoptic, and diurnal time scales do have a direct influence on the small scale horizontal sea surface temperature structure. The finding of different temporal scales in the horizontal sea surface temperature variance help to explain the inconsistencies between earlier observational and theoretical studies.

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